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Rural electrification with household wind systems in remote high wind regions

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ABSTRACT

This paper offers a comparative analysis of small wind electrification programmes targeted at remote sheep farming households in two of the windiest regions of the world, Argentine Patagonia and the Falkland Islands/Islas Malvinas. Despite comparable environmental conditions and local livelihoods, their impact was vastly different. Insights from socio-technical systems and strategic niche management approaches offered a deeper understanding of the local context and development dynamics, facilitating the identification of the critical success factors that contributed to these two distinct outcomes and finally highlighting those that can inform the design of future such initiatives. The research is based upon a series of semi-structured interviews with key stakeholders, observational field visits and review of archival sources. The critical factors identified by this case study research include strong and consistent institutional support, investment in robust equipment creation of effective feedback loops from the field and hybridisation. Additionally, a user centred approach that assesses whether small wind is really the right option for each individual household and if so, matches an appropriate energy system to their unique and evolving needs. Finally, empowering users to take on as much responsibility for maintenance as possible by integrating maintenance practices with local culture and ensuring the support of an effective decentralised maintenance network.

Introduction

Today 1.1 billion people's homes are still not connected to grid electricity; decentralised renewable energy is playing an increasingly important role in meeting this challenge (IEA, 2017). Over the past few decades, the rapid growth of the large-scale wind power industry,[2] innovations in the off-grid sector, the steadily increasing prices of fossil fuels and concern over their environmental impacts have created a global renaissance for small scale wind energy. Nevertheless, the technology still faces a range of social, economic, organisational, political and technical challenges, which require not only further technological development, but also deeper insight into the critical factors that can enable and constrain more widespread dissemination and greater social impact (Clementi, 2018; Ferrer-Martí et al., 2010; Kamp & Vanheule, 2015; Terrapon-Pfaff, Dienst, König, & Ortiz, 2014).

The powerful winds that whip around the Southern Ocean create some of the most favourable conditions for wind power generation anywhere in the world (Fig. 1). The clear predominant wind direction (south-westerly) and the vast steppe landscapes of Chubut and the Falkland Islands/Islas Malvinas offer high and evenly distributed winds at low hub heights (Gallegos, 1997; Moragues & Rapallini, 2003; Oliva, 2008; Spinadel, 2015). In both regions, many remote sheep farming households (HHs) are too isolated for grid connection, leaving decentralised power generation as the only viable option for electricity access (Clementi, Jacinto, & Carrizo, 2014; H. Mattio & Franco, 2002). The global decline in wool prices hit sheep farmers hard, with many leaving their rural homes to nearby grid-connected settlements where basic services such as electricity were already available. In an attempt to stem this flow of people, a considerable number of Household Wind Systems (HWS) have been installed in recent decades, in order to open up greater opportunities to improve the quality of life of the scattered rural population. These HWS are the subject of this investigation.

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[1] Subsequently transferred to *School of Social Science*, Loughborough University, Leicestershire LE11 3TU, UK.
[2] Raises awareness that generating power from the wind is possible and often also results in the development of supporting resources such as wind maps.

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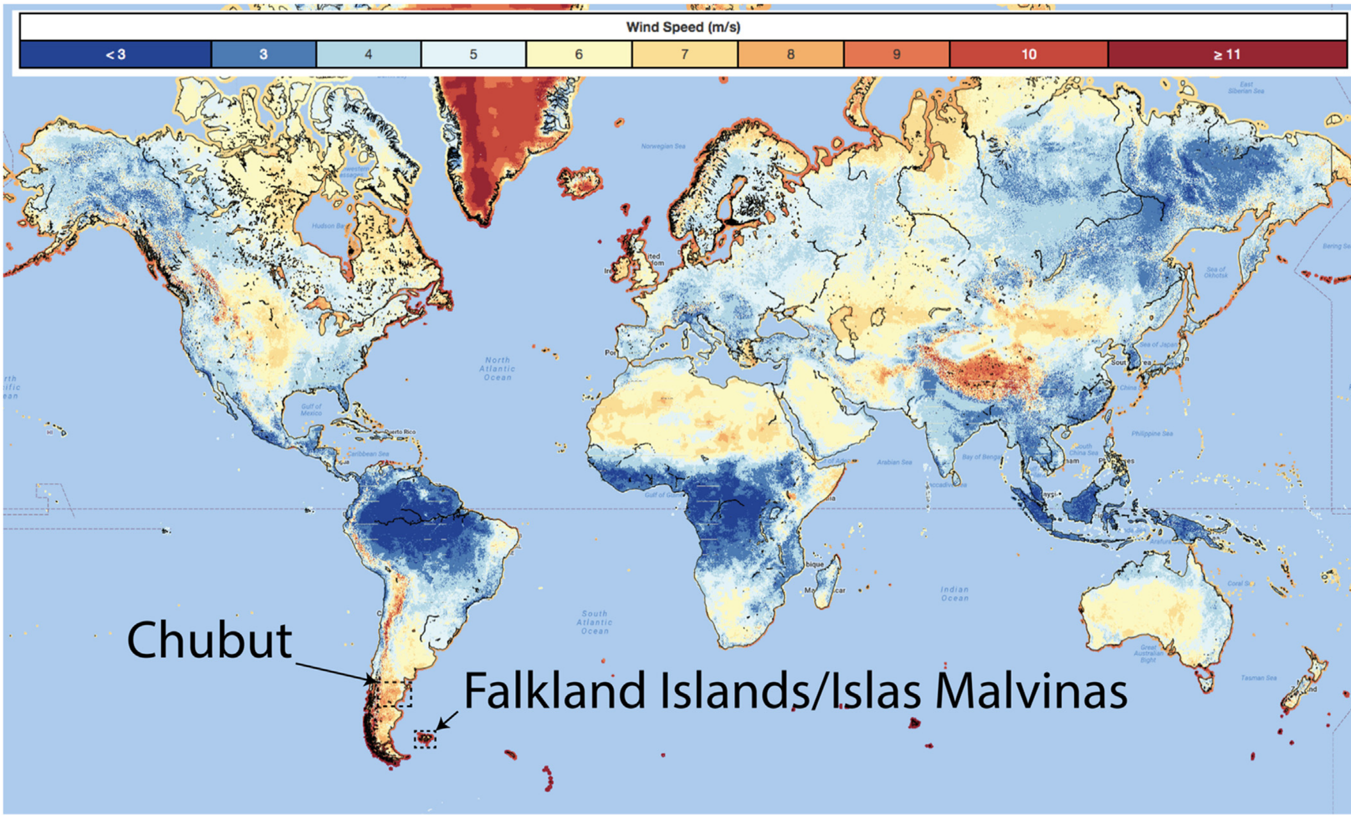

Fig. 1. Global wind atlas at 50 m height showing high wind potential in Chubut and the Falklands/Malvinas. Dataset: DTU Wind Energy's (2017) Global Wind Atlas, overlaid on Google Maps base layer.

In the 1930s/40s/50s, 12 V Lucas Wind Chargers, multi-bladed mechanical wind pumps and kerosene-fuelled 'tilly lamps' were standard issue in farms across both regions. Petrol-fuelled Villiers lighting sets offered rudimentary electric lighting to some; however, their capacity was extremely limited, so the arrival of diesel generating sets and cheap fuel in the 1960s opened up a whole new range of energy services. However, in the subsequent decades, increasing oil prices renewed interest in wind energy.

The successful dissemination of over 100,000 HWS across the vast windswept plains of Inner Mongolia has shown that where suitable environmental conditions exist and appropriate social infrastructure is established, the technology can make a valuable contribution to the development of remote regions (Barley, Lew, & Flowers, 1997; Batchelor, Scott, Daoqi, & Bagen, 1999; Xiliang, Gan, Shuhua, & Wenqiang, 1999). Whilst much research has focussed on adapting SWTs to the globally vastly more abundant low wind regions (Ferrer-Martí et al., 2010; Khennas, Dunnett, & Piggott, 2008; Watson et al., 1999), the recent dramatic fall in the price of PV (Photovoltaic) modules (IRENA, 2016) means that Small Wind Turbines (SWTs) can no longer compete in these contexts and are now seen as an option for the hybridisation of PV systems (Glassbrook et al., 2014; Leary et al., 2018; Sumanik-leary et al., 2016). Maintenance requirements are much higher and the high spatial variation in the resource significantly limits the scalability of wind-based electrification programmes (Sumanik-leary, While, & Howell, 2013).

Many studies have recognised the lack of maintenance as one of the key barriers preventing renewable energy development initiatives from achieving their intended development impact. The quality of the installed equipment (Kamp & Vanheule, 2015), the severity of local environmental hazards (Carvalho Neves, Gleditsch, Bennet, Craig, & Sumanik-Leary, 2015) and the quality/frequency of preventative maintenance (Ellegård, Arvidson, Nordström, Kalumiana, & Mwanza, 2004) can dramatically influence the failure rate. Many authors point out the high transportation costs of sending trained personnel out to remote areas (Laufer & Schäfer, 2011; Sovacool, D'Agostino, & Jain Bambawale, 2011), particularly in comparison to the low tariffs appropriate for poorer HHs (Kobayakawa & Kandpal, 2014). When each trip can cost more than the equipment itself, the use of standardised parts becomes critical (Rahman, Paatero, Poudyal, & Lahdelma, 2013). Berger (2017), Morales et al. (2015) and Chaurey and Kandpal (2010) illustrate the importance of not only training end-users, but also ensuring they are familiar with the institutional practices required to obtain after-sales service. Berger (2017) also cite the lack of clear responsibility for the systems, lack of equipment for maintenance work and the very slow and unreliable chain of information in case of system failure as key challenges. Rahman et al. (2013) and Rupf, Bahri, De Boer, and Mchenry (2015) note the importance of ownership on the motivation of end-users to carry out maintenance, even when adequate training has been carried out.

Other than the well-studied case of Inner Mongolia (Barley et al., 1997; Batchelor et al., 1999; Xiliang et al., 1999), the literature review revealed a lack of studies on the long-term sustainability of HWS in remote high wind regions. Kamp and Vanheule (2015) used Strategic Niche Management to analyse the emerging Kenyan SWT industry, as did Schaube, Ortiz, and Recalde (2018) with the decentralised renewable energy niche in Argentina. However, the authors are unaware of any studies focusing recently developed socio-technical transitions theory (Geels, 2005; Kemp, Schot, & Hoogma, 1998) onto the problem of developing sustainable social infrastructure to support the high maintenance requirements of HWS.

Consequently, this paper seeks to answer the research question '*what are the key socio-technical factors that can lead to the establishment of sustainable social infrastructure to support small wind electrification programmes in remote high wind regions?*' by:

1. Determining the impact of HWS in Chubut and the Falklands/Malvinas.

2. Using a socio-technical transitions lens to comparatively analyse the two distinct approaches to maintenance services.
3. Identifying the key factors for future small wind rural electrification programmes in remote high wind regions.

Case study sites

Background information

1.1 million rural Argentines live off-grid, the vast majority of whom rely on firewood, kerosene/gas, disposable batteries and/or generating sets for their basic energy needs (IEA, 2014). In 1999, the Argentine government launched PERMER[3] to provide renewable electricity access to off-grid public institutions and HHs (Haselip, Nygaard, Hansen, & Ackom, 2011). According to official statistics, the installation of 29,980 systems with a capacity of 8.15 MW and an average annual generation of 19.8 GWh have allowed over 100,000 rural Argentines to gain access to electricity through this initiative (World Bank, 2015).

In recent years, strong political support for local industries has fostered the development of 16 Argentine SWT manufacturers (Figel, 2012; INTI, 2012; Schaube et al., 2018; Soares, Kind, & Fernández, 2009; Spinadel, 2015). As a result, the vast majority of Argentina's estimated 8500 SWTs with a total installed capacity of 6 MW and individual capacities between 150 W and 10 kW have been manufactured within the country (INTI, 2012; WWEA, 2013).

The province of Chubut is situated between 42 and 46° latitude, with the Andes forming a natural border with Chile to the west and the Atlantic Ocean to the east. Historically, the province's main economic activity was sheep farming, however today oil and gas, agriculture, industrial processing and Atlantic fishing all contribute significantly (World Bank, 2015). 70% of Chubut's 500,000 inhabitants live in coastal or Andean cities, leaving the vast central region (224,686 km^2) sparsely populated. It is characterised by a high percentage of indigenous communities and a lack of infrastructure (Hector Mattio, 2002).

Spearheaded by CREE,[4] Chubut gained a positive reputation for rural electrification by harnessing the provinces' powerful winds. This began with the installation of wind-diesel hybrid systems in rural school villages[5] from 1989 onwards and was followed by 300 HWS installed in indigenous communities[6] from 1997–2000 (H. F. Mattio, 2013; Hector Mattio, 2002).

However, preliminary market assessments for PERMER-Chubut revealed 3857 rural HHs still without electricity access (PERMER, 2001). Under Phase I of PERMER-Chubut in 2003, 100 Aerowind SWTs were installed in the indigenous communities of Pocitos de Quichaura and Costa de Ñorquinco, plus a further 19 in protected areas and border crossings (H. F. Mattio, 2013). However, failure rates in the extreme Patagonian environment were high and Aerowind S.A. failed to offer maintenance services, so almost all were subsequently replaced. As a result, when World Bank financing became available to scale-up the initiative in 2003, the tender was reopened, and Giacobone S.A. of Cordoba was selected as the equipment provider. Giacobone partnered with the Chubutense company, Incro S.A., who were to install and maintain the solicited 1500 Eolux HWS during the first two years of operation, handing over responsibility to the DGSP's[7] Eolo Chubut. Installation of Phase II of PERMER-Chubut took place between 2008 and 2010. According to official information, a total installed capacity of 810 kW now provides electricity to 6000 people, leaving just 1490 HHs without electricity access (World Bank, 2015) .

The Falkland Islands/Islas Malvinas are a South Atlantic archipelago with a total land area of 11,650 km^2, consisting of two main islands (East and West Falkland) and over 700 smaller islands. The islands are situated 500 km from the Patagonian coastline from 51 to 53° latitude. The sovereignty of the Falkland Islands/Islas Malvinas is currently disputed between Argentina and the UK, with the islands governed as a British overseas territory.[8]

Over 2000 of the islands' 2900 inhabitants live in the capital, Stanley, which is powered by a 6 MW diesel and 2 MW wind hybrid mini-grid. The remaining population is scattered across the islands, relying on micro-grid or off-grid systems for electricity access. The Falkland Islands Development Corporation (FIDC) is the commercial division of the Falkland Islands Government (FIG), with the mission to "*encourage and assist all aspects of local business*" (Cotter, 1999).

Until recently, almost all farms used peat[9] for space heating and cooking. Just as the Land Rover became the islands' standard vehicle, Lister generating sets proliferated from the 1960s onwards. Smaller farms operated 3–20 kW isolated systems, whilst larger settlements would operate micro-grids with a centralised 20–100 kW generator. However, power was generally only available for several hours in the morning and evening, as operating diesel generators at low load is extremely inefficient and greatly accelerates wear. Increasing oil prices drove local farmers and the FIDC to investigate SWTs and battery-inverter systems to reduce fuel consumption.

In 1988, Clive Wilkinson imported a Trace Power Centre and the first modern SWTs into the islands, experimenting with a range of equipment to find out what could survive the extreme conditions. Most SWTs were blown to pieces in months, weeks or sometimes even days. During the early 90s, the FIDC installed various PV-wind-diesel hybrid configurations at Pebble Island and Estancia, carefully monitoring power production with datalogging equipment. Meanwhile, Clive Wilkinson founded Powersense and in 1995, pioneered the winning combination of Proven SWTs, Trace SW Power Centres and Chloride Motive Power batteries at Darwin Head. Seamless wind-diesel integration offered farms a reliable and affordable 24-hour power supply. After a year of successful operation, Tm Cotter and the FIDC's Energy Advisory Committee designed a grant scheme to allow the 80+ small farms across the islands to purchase comparable systems at highly subsidised prices. The key actors is each context are summarised in Figs. 2 and 3, whilst Fig. 4 shows the small wind systems they promoted.

HWS promoted in Chubut and the Falkland Islands/Islas Malvinas

Fig. 5 and Table 1 compare the HWS promoted under the PERMER programme in Chubut and the FIDC Small Farms programme in the Falklands/Malvinas. In the Falklands/Malvinas, the high initial purchase price (averaging $37,000 in 2008 USD) was heavily subsidised by the FIDC in two phases: battery/inverter 24 h power system (50%), then SWT (70%). However, users were entirely responsible for maintenance/fuel costs and generator/appliance purchase costs. The subsidy was available for two system sizes,[10] matched to each HH's current demand on their diesel system. In Chubut, all systems were identical[11] and no inverter was included (although it was expected that many users would later add this as an optional upgrade). Instead, standardised 12 V DC HH

[3] *Proyecto de Energías Renovables en Mercados Rurales* - Renewable Energy in Rural Markets Project.

[4] *Centro Regional de Energía Eólica* – Regional Centre for Wind Energy, part of the *Dirección General de Energías Renovables* (DGER) – Department for Renewable Energy.

[5] 600 W–4.5 kW Argentine (Eolux and Agroluz) and imported (Whisper) SWTs under the *Mejoramiento de la Calidad de Vida en Aldeas Escolares del Interior Chubutense* - Improvement in Quality of Life in School Villages in the Interior of Chubut programme.

[6] *Electrificación de Pobladores Rurales y Mejoramientos de Vivienda en Comunidades Aborígenes* – Rural Electrification and Household Improvements in First Nation Communities programme.

[7] *Dirección General de Servicios Públicos* – Department for Public Services.

[8] The islands have internal self-governance, whilst the United Kingdom is responsible for defence and foreign affairs. This paper does not seek to enter into the sovereignty debate, instead taking a neutral stance and only commenting on political factors when directly relevant to the uptake of HWS.

[9] A semi-renewable fuel consisting of partly decayed organic matter that is found in abundance across the islands.

[10] 2.5 kW SWT with either a 3 kW inverter & 48 V 330 Ah battery bank or 4.2 kW inverter & 48 V 600 Ah battery bank.

[11] 500 W SWT feeding a 220 Ah 24 V battery bank.

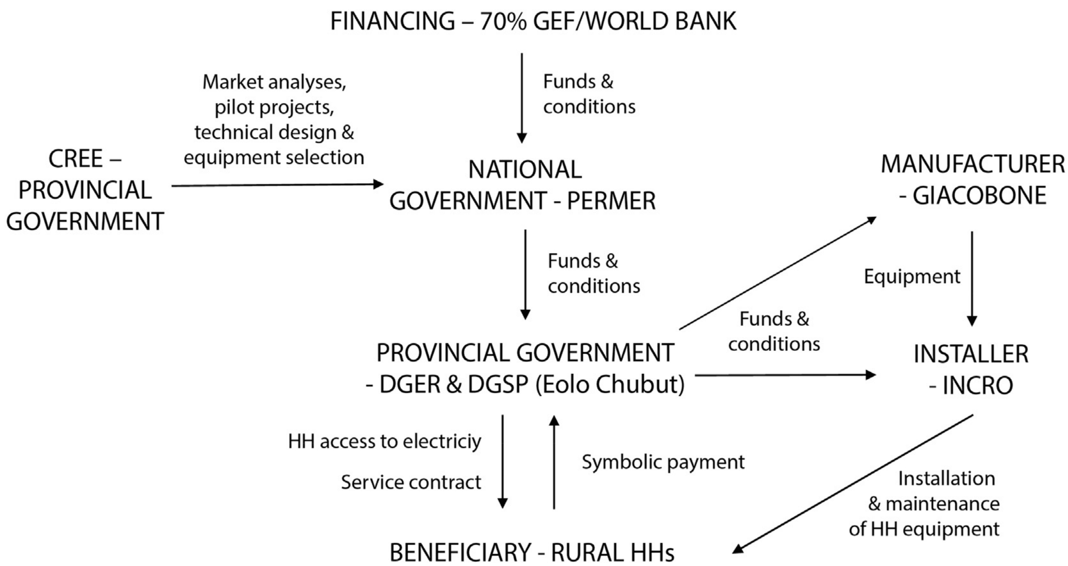

Fig. 2. Key actors and roles in Phase II of PERMER-Chubut.

installations included power sockets, 6 fluorescent tube lights and a radio. A sliding scale of tariffs for ranging from AR$400–800/yr ($126–252 in 2008 USD/yr) for connection and AR$300–480/yr ($94–151 in 2008 USD/yr) for maintenance was to be collected during biannual maintenance inspections. However, even though the initial purchase cost was far lower than in the Falklands/Malvinas ($6513 in 2008 USD), at just 2–4%, user contributions were merely symbolic.

Theoretical framework

This research draws upon two recently developed theoretical frameworks from innovation and sustainability studies that are capable of breaking down the complex, multi-dimensional nature of energy systems. Specifically, socio-technical systems (Geels, 2005) and strategic niche management (Kemp et al., 1998) from the multi-level perspective (Geels, 2011) are combined to frame HWS as an emerging technological solution to a social problem: the lack of access to energy services in remote areas.

Firstly, the socio-technical systems approach allows us to understand both the "*social 'software'*" and "*technical 'hardware'*" (Sovacool et al., 2011, p. 1534), as well as the interlinkages between the two. In this approach, technology is seen as a product of social shaping, situated within the co-evolution and co-production of human and non-human actors (Geels, 2005). In this context, a HWS can be seen as a socio-technical system, in which strongly interlinked social and technical aspects (e.g. ownership of technology or technical training) enable or constrain their ability to fulfil their societal function. This socio-technical lens gives equal importance to the roles of technicians, politicians and end users as the functionality of generators, inverters and batteries (Sovacool et al., 2011).

Secondly, the multi-level perspective defines three levels (Geels, 2011):

1. *The landscape*: is "*characterized by large-scale developments and long-term trends which can hardly be influenced by individuals or groups of actors*" (Schneidewind & Augenstein, 2012). Changes generally occur more slowly than at the regime level, as it consists of a set of heterogeneous factors such as macro-economics or political systems (Geels, 2011). In this study, landscape level influences include local geography, changes in global fossil fuel prices and increased global action to combat climate change.

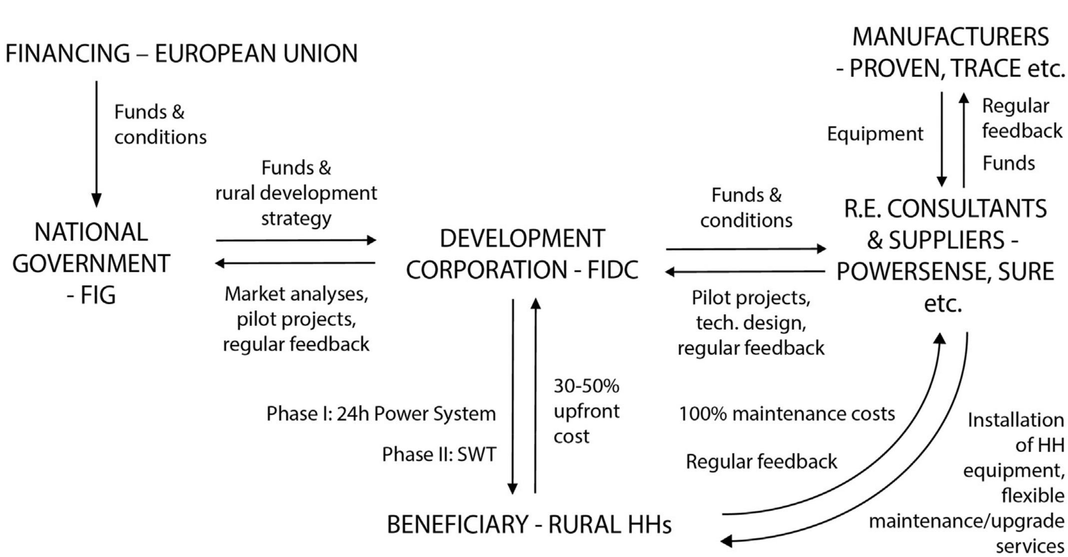

Fig. 3. Key actors and roles in the FIDC rural energy grant scheme in the Falklands/Malvinas.

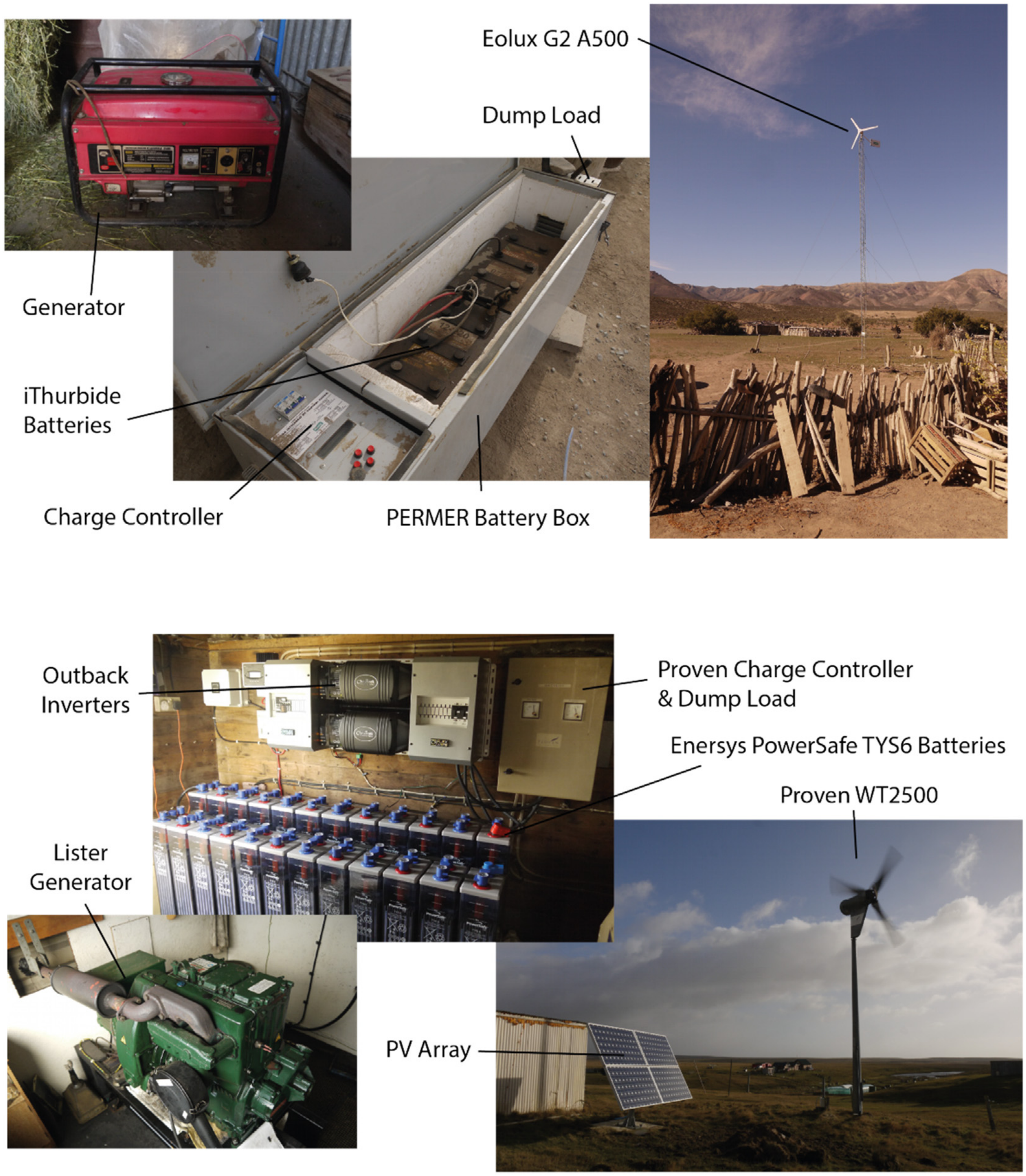

Fig. 4. Photographs of typical HWS installations in Chubut (above) and the Falklands/Malvinas (below).
(Photos by Jon Leary in 2014.)

2. *The regime*: or the mainstream way of doing things in a specific place (Hermwille, 2016). This study uses Holtz, Brugnach, and Pahl-Wostl's (2008) broad conceptualisation of the 'regime', to mean the centralised electricity generation and distribution network in Chubut and the Falklands/Malvinas.
3. *Protected 'niche' spaces*: this is where new technologies/practices are developed (Johan & Geels, 2008). This study investigates the development of decentralised HWS in protected 'niche' spaces and their attempts to breakthrough into the regime and become the mainstream way of accessing electricity for rural people in Chubut and the Falklands/Malvinas. This process can be guided by insights from strategic niche management (Kemp et al., 1998).

Within the strategic niche management approach progress of sociotechnical niches is conceptualised as a cyclical pattern of learning and networking in which cognitive rules are consolidated (Johan & Geels, 2008). The process can be understood as taking place on two levels: local and global (Geels & Deuten, 2006). The local level consists of individual projects, where actors experiment with innovative ways of responding to local problems and demands. The development of a global niche requires the aggregation of lessons learned from individual projects (Johan & Geels, 2008; Seyfang, Hielscher, Hargreaves, Martiskainen, & Smith, 2014). With each application of the emerging technology in new places, actors gain knowledge about the viability of the technology and its compatibility with specific contexts (Kemp et al., 1998).

Focussing a socio-technical lens at the local project level enables the disentangling of the intertwined social, technical, economic, political and organisational factors that have contributed to the successes and failures of the electrification programmes in Chubut and the Falklands/Malvinas. The strategic niche management and the multi-level approach complements this by enabling the internal (resulting from the niche level) influences to be

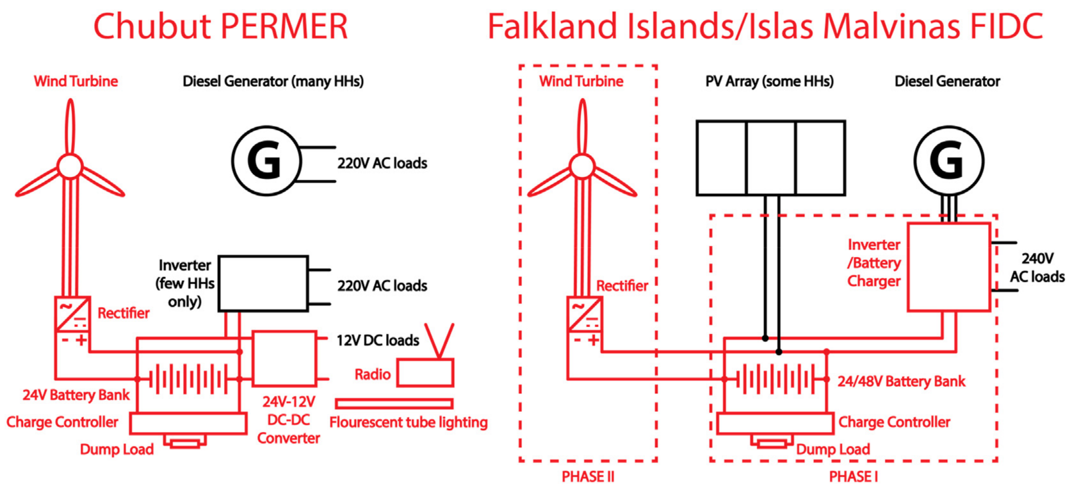

Fig. 5. Schematics of the HWS discussed in this paper. Red indicates standardised components in all systems, whilst black indicates pre-existing or potential future additional components added at the user's discretion. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

distinguished from the external (resulting from the interaction with the broader regime and landscape levels). This facilitates the identification of key pathways for HWS to break through from protected 'niche' spaces and into the regime, thereby becoming a mainstream solution for remote un-electrified HHs in high wind regions.

Table 1
Technical comparison of a single typical FIDC small farm system in the Falklands/Malvinas with the standardised PERMER system in Chubut.

System component	FIDC small farms			Chubut PERMER		
	Technical specification	Cost (2008 USD)[d]	Subsidy	Technical specification	Cost (2008 USD)[e]	Subsidy
Total (not inc. user purchased appliances)		$36,528	$21,925		$6513	$6324
SWT						
- Model	Proven WT2500[a]	$10,055	70%	G2 A500	$1458	97%
- Rated power/rpm	2.5 kW @12 m/s			500 W @12 m/s		
- Rotor	3.5 m diameter, 3 bladed HAWT, downwind			3 bladed HAWT, upwind		
- Protection from extreme winds	Coning mechanism & manual brake			Manual brake		
Tower	6.5 m monopole tilt-up	$4048	70%	12 m guyed lattice	$699	97%
Battery bank	Chloride Motive Power[b] 2 V wet lead acid cells in 330 Ah or 660 Ah 24/48 V banks	$7964	50%	2x iThurbide 12–220 in 220 Ah 24 V bank	$746	97%
Charge control	Proven charge controller, dump load & rectifier	$3141	70%	Charge controller, dump load & rectifier[f]	$272	97%
Power converters	3 or 4.2 kW 240 V AC from Trace Power Centre (SW3024/48E or SW4248E)[c]	$7770	50%	24–12 V DC-DC converter with 12 V DC outlets standard. Inverter optional user upgrade.	$15	12 V DC: 97% Inverter: 0%
Datalogging	E-meters	$500	50%	Custom datalogger[f]	$298	97%
Installation hardware	Power cable, fuses, cement base, junction boxes, switches.	$1627	50–70%	Power cable, fuses, cement base & anchor points, junction boxes, SoC (State of Charge) indicator, switches.	$1176	97%
Installation labour & shipping	Equipment: sea freight to Stanley, road/boat to site. Installer: labour & road/air travel to site.	$1421	50–70%	Equipment: road to warehouse in Chubut, overland to site. Installer: labour & road travel to site.	$1596	97%
Generator	Lister diesel generator at all HH. Typically TS2 6 kW.	$6000	0%	1–6 kW petrol or diesel generator at majority of HH. Typically 2.5 kW.	$252	0%
HH appliances						
- Included	–	–	–	6x fluorescent lights & radio	$288	97%
- Typically purchased by users	Lights, central heating system (kerosene/diesel), TV, radio, computer, washing machine, tumble dryer, power tools, shearing equipment, wool press.	–	0%	If inverter and/or generator purchased by user: TV, power tools, additional lights.	–	0%

[a] Initially sold as WT2200 before upgrading windings and blades. Later rebranded as Kingspan 2.5 kW, then KW3.
[b] Later replaced by Enersys PowerSafe TYS6, which are lighter & have greater water storage capacity.
[c] Later replaced by Outback 3 kW modular inverter/battery chargers.
[d] Costs averaged across 6 representative systems (both 3 kW inverter, 300 Ah battery and 4.2 kW inverter, 600 Ah battery) and converted from GBP in actual year of installation to 2008 USD.
[e] Costs directly converted from Giacobone/Incro offer in 2008 public tender for 1500 HWS in EUR and converted to 2008 USD.
[f] Supplied as an integrated unit manufactured by Giacobone specifically for the PERMER programme.

Table 2
List of key stakeholders interacted with during this research study. Reference codes are used in the tables in the Critical factors section.

Reference code	Stakeholder	Sector	Data collection	Data collected by	Location
FK1	FIDC	Public sector	Interview, archival sources	JL	Stanley
FK2	FIG	Public sector	Interview, archival sources	JL	Stanley
FK3	PowerSense	Private company	Interview, observational field visits	JL	Stanley & selected East Falkland farms
FK4	Stanley Power Station	Utility	Interview, observational field visits	JL	Stanley power station & wind farm
FK5	Falkland Island farmers	End-users	HH interviews, observational field visits	JL	Stanley & selected East/West Falkland farms
FK6	SURE	Private company	Interview & observational field visits	JL	Stanley & selected East/West Falkland farms
CH1	Eolo Chubut, DGSP	Public sector	Interview, archival sources, observational field visits	JL & PS	Rawson, Las Plumas
CH2	PERMER	Public sector	Archival source, presentation, group discussion	JL	Buenos Aires
CH3	Chubutense farmers	End-users	HH interviews, questionnaires, observational field visits	JL & PS	Las Plumas, El Molle, Cerro Gorro Frigio
CH4	500 RPM	NGO	Interview, observational field visits, participation in wind turbine fabrication course, SWT workshop	JL & PS	Córdoba, Bariloche, Buenos Aires
CH5	INTI	Public sector	Interview archival sources observational field visits, facilitated discussion at annual small wind manufacturers symposium, SWT workshop	JL & PS	Buenos Aires & INTI Cultral-Có test site
CH6	La Escuela Nuestra Señora del Valle	NGO	Observational field visits, participation in wind turbine fabrication course, SWT workshop	JL	Cholila
CH7	Giacobone	Private company	Interview	JL & PS	Buenos Aires
CH8	Cooperativa de Luz	Utility	Interview	JL	El Maitén
CH9	CREE	Public sector	Interview, archival sources	JL & PS	Rawson
CH10	UNPA	University	Interview, SWT workshop	JL	Rio Gallegos
CH11	Ingeniería Sin Fronteras Patagonia	NGO	Observational field visits, archival sources, SWT workshop	JL & PS	Comodoro Rivadavia, Cerro Gorro Frigio, El Molle
CH12	AAEE	NGO	Interview, archival sources	JL & PS	Buenos Aires

Methodology

Data collection

This research is based on a series of semi-structured interviews with key stakeholders, observational field visits and the review of archival sources (summarised in Table 2). Relevant sources included project planning/evaluative reports, external presentations and system design calculations. Data collection ceased when the saturation point was reached in each context, i.e. the findings of new investigations began to repeat what had already been discovered.

Key stakeholders included HHs, community leaders, maintenance providers, programme designers, SWT manufacturers, policy makers and other local small wind experts. Initial contact with gatekeepers (see Discussion) opened the door to each context, enabling further key stakeholders to be identified using snowball sampling strategies[12] (Laerd, 2015). For the interviews with end users during observational field visits,[13] an interview guide was developed to ensure key topics were discussed (dominant energy practices, familiarity with different technologies etc.) and to make it possible to pick out key trends. The interviews with key stakeholders revolved around questions specific to their roles. Both sets of interviews also included an unstructured element, allowing the participants to guide the researchers towards issues they felt were of particular relevance. Whenever possible, interviews were recorded and later transcribed; otherwise notes were taken and later written up.

The research also included an element of participant observation, e.g. participation in routine field visits to carry out maintenance on HWS. Field diaries captured rich ethnographic data in written and photographic form. Observational field visits were undertaken at remote farms, service centres and local authorities. During the field visits, data was collected on the life history of each HH energy system, resulting in the construction of a timeline showing the uptime of each system component. Although useful to evaluate the reliability of the equipment employed, this form of questioning opened up a much broader dialogue on user preferences, access to maintenance services, the perceived value of the system, future plans for upgrading and expanding, access to finance, technical capabilities etc. Interviews with end users took place in their homes, allowing them to demonstrate the role of each piece of equipment in everyday life.

Fig. 6 shows the location of the 22 HHs visited in Argentina and the 21 visited in the Falklands/Malvinas. Due to logistical challenges and time restrictions, HHs in both locations were selected for interview with the aid of gatekeepers. Whilst the number of HHs visited may be insufficient for formal statistical analysis, interviews with other relevant stakeholders were used to determine whether the trends picked up in the field visits were representative of the entire programme. Data was collected in the Malvinas/Falklands by J. Leary, whilst both J. Leary (Cerro Gorro Frigio and Las Plumas) and P. Schaube (El Molle) collected data in Chubut.

Data analysis

Qualitative content analysis techniques were applied to the textual material generated from encounters during field work and interviews with key stakeholders. Gibson and Brown (2009) describe how a priori codes defined from top-down theory can function as analytical categories or code families. These can be complimented by empirical codes, arising from the exploration of data. In this study, the socio-technical framework (Geels, 2005; Sovacool et al., 2011) defined five a priori categories: organisational, social, technical, economic and political. During the data analysis process, the field diaries, interview notes and transcripts were reviewed by J. Leary and P. Schaube in a structured process designed to draw out and categorise the critical success factors (empirical codes) in each context (Fig. 7).

After initial examination of the data, the preliminary results suggested that elements of the strategic niche management framework could offer greater insight into the complex dynamics observed.

[12] Requesting interviewees to recommend other relevant candidates for interview.

[13] To get access to the disperse settlements in Chubut, the researchers relied on the support of the NGO "Ingeniería Sin Fronteras Patagonia" (El Molle, Cerro Gorro Frigio) and the DGSP (Las Plumas), who determined the selection of the case study sides. In the Falkland Islands, Tim Cotter of the FIDC and Clive Wilkinson of PowerSense performed a similar role.

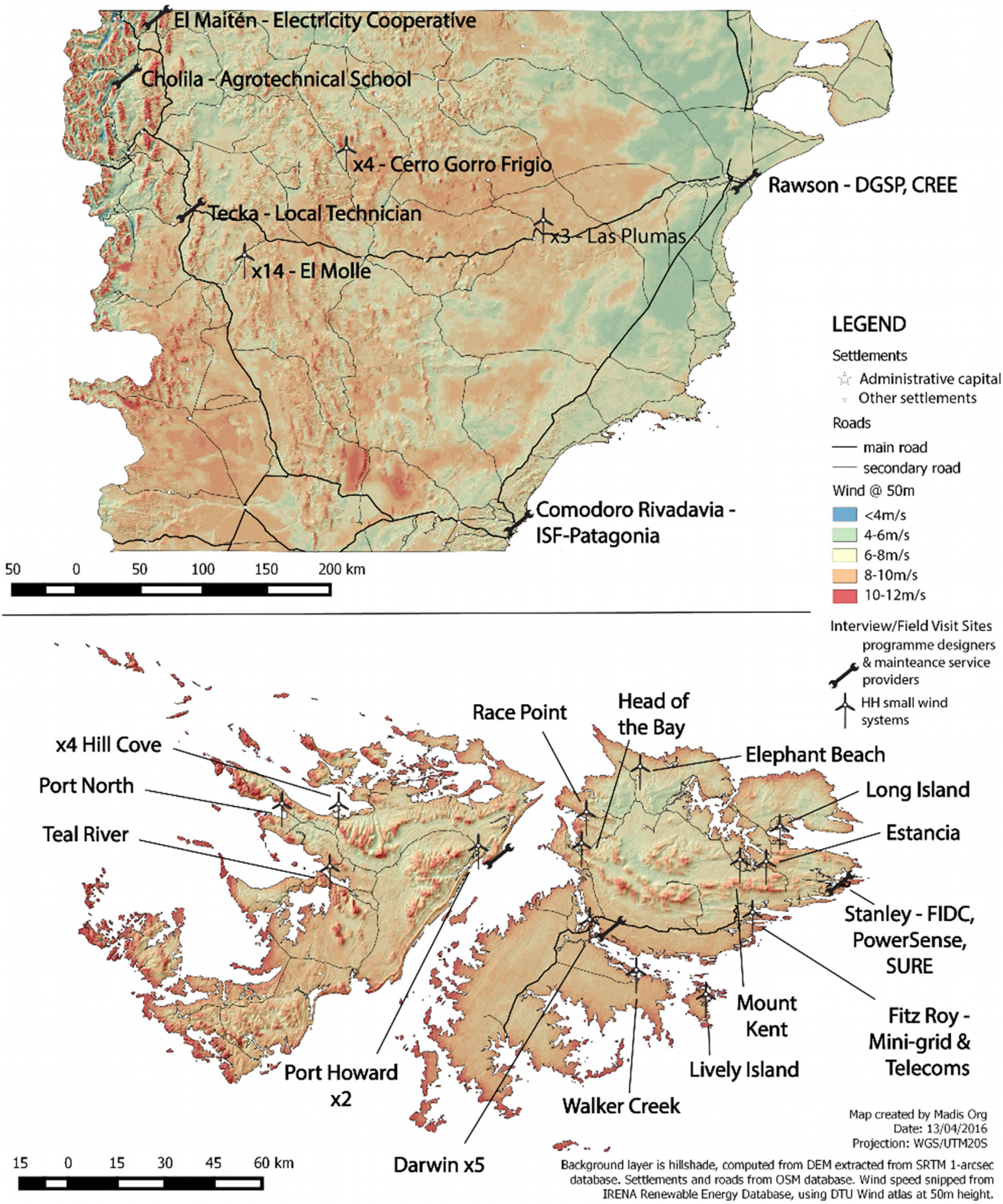

Fig. 6. Interview and field visit sites in Chubut (above) and the Falklands/Malvinas (below). Base layer of wind resource map from 50 m DTU Global Wind Atlas (DTU Wind Energy, 2017).

Consequently, the niche, regime and landscape levels of the multi-level perspective were employed as supplementary a priori codes in a second round of analysis. This iterative process of deductive category application and inductive category development based on the cyclical interaction of empirical and a priori codes (Kuckartz, 2014; Mayring, 2000) enabled a much deeper exploration of the data using both the theoretical insights from the socio-technical transitions literature and the emerging findings from both case studies.

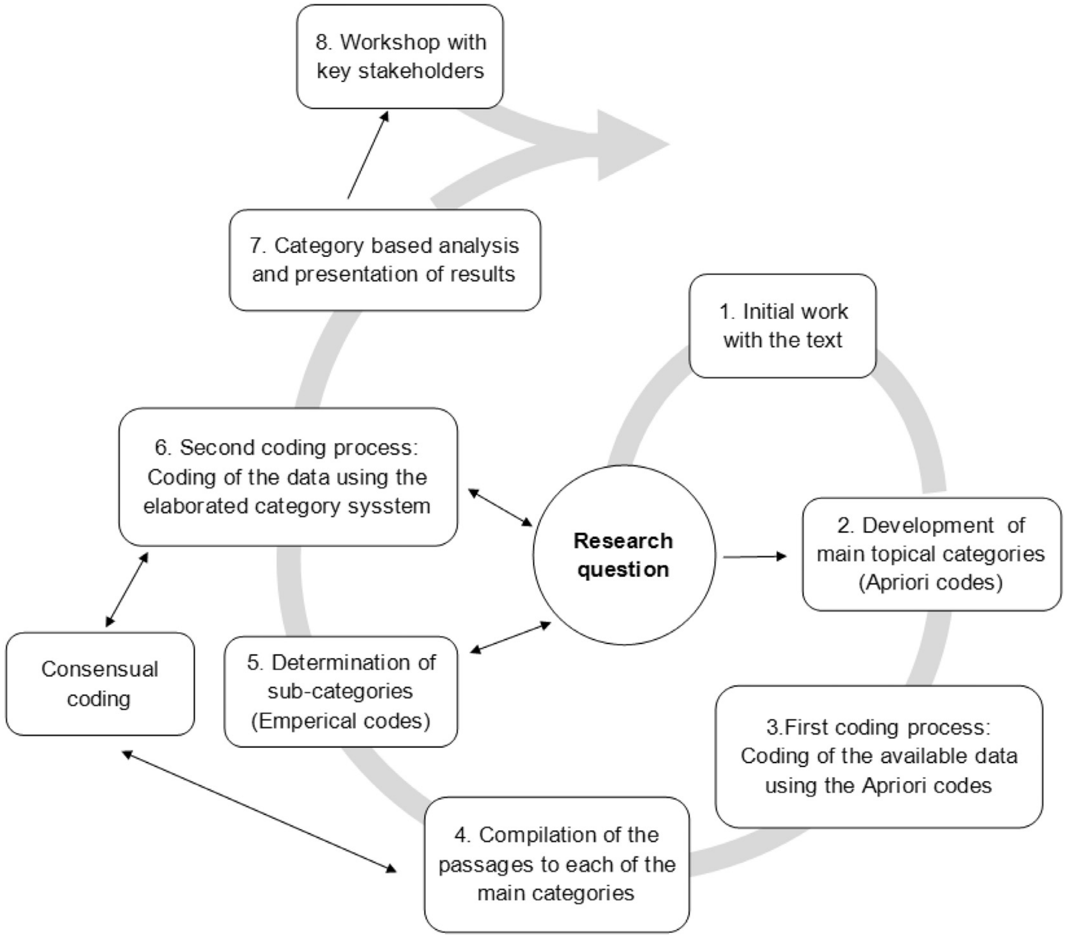

Fig. 7. Overview about the interview data analysis and the research process.
(Own illustration, based on Kuckartz (2014).)

The ATLAS.ti computer programme was used for the qualitative content analysis to uncover and systematically analyse complex phenomena hidden in the textual data. Firstly, phrases were independently categorised by the international and interdisciplinary research team (authors of this article) in a double-blind analysis. To enhance the reliability of the coding in the next step, the coding results were checked for similarities and differences based on the consensual coding process described by Kuckartz (2014).

In an attempt to create more robust knowledge, preliminary results were presented and discussed in a small wind workshop in Argentina (Leary, Schaube, & Clementi, 2016) with a transdisciplinary mix of participants (including many of the key stakeholders already interviewed for this research) and to the PERMER team (Leary, Schaube, & Clementi, 2017). In addition, English and Spanish versions of the article were later sent out to all key stakeholders, ensuring that those who were not able to attend either of the discussion sessions still had an opportunity to comment on the findings. As a result, the findings of this study can be seen as a product of continuous inductive exchange with real word actors.

Results

Development impact of HWS

In both contexts, improvements in quality of life were highly valued by end users. However, the impact of these new/improved energy services was vastly different, most fundamentally due to the time that each HWS was operational. In the Falklands/Malvinas, HWS had a broad and positive impact across the entire farming community.

> "It would be quite tough to go back now…It used to be very much hand to mouth…You went out and did your work and came in all wet and dirty. The first thing you did was get the peat going so you'd have enough hot water for a bath…It may have made it cheaper, but it's the quality of life that we really value."
>
> [Falkland Island Farmer & FIDC Beneficiary, August 2014]

An estimated 85% of the 80+ small farms use FIDC-subsidised wind-diesel hybrid systems as their primary source of electricity. Fig. 8 shows an average availability of over 94%, a Mean Time Between Failures (MTBF) of almost 4 years and a Mean Time To Return (MTTR[14]) of 26 days, indicating that with regular maintenance, HWS can offer reliable access to electricity. Each farmhouse has at least one generator, which is seamlessly interfaced into the 24 h power system, ensuring that total blackouts are almost unheard of.

In contrast, whilst the energy services offered by HWS in Chubut were highly valued by users, the potential impact of PERMER-Chubut was vastly diminished by excessive downtime. Fig. 8 shows an availability of 54% in Las Plumas, 75% in Cerro Gorro Frigio, and under 60% in El Molle (see footnote on Fig. 8). Only 5 of the 22 HWS visited by the researchers in Chubut were operating at the time of the field visits. Although only a relatively small number of the 1500 HWS could be visited during this study, the interviews with other key stakeholders confirmed that the trends observed were representative of the entire programme, the root causes of which are described in the *Critical factors* section. The lack of access to maintenance services has been extremely frustrating to end users, many of whom have been unable to use the system for many years due to

[14] The average length of time taken to repair a fault and get the HWS back online.

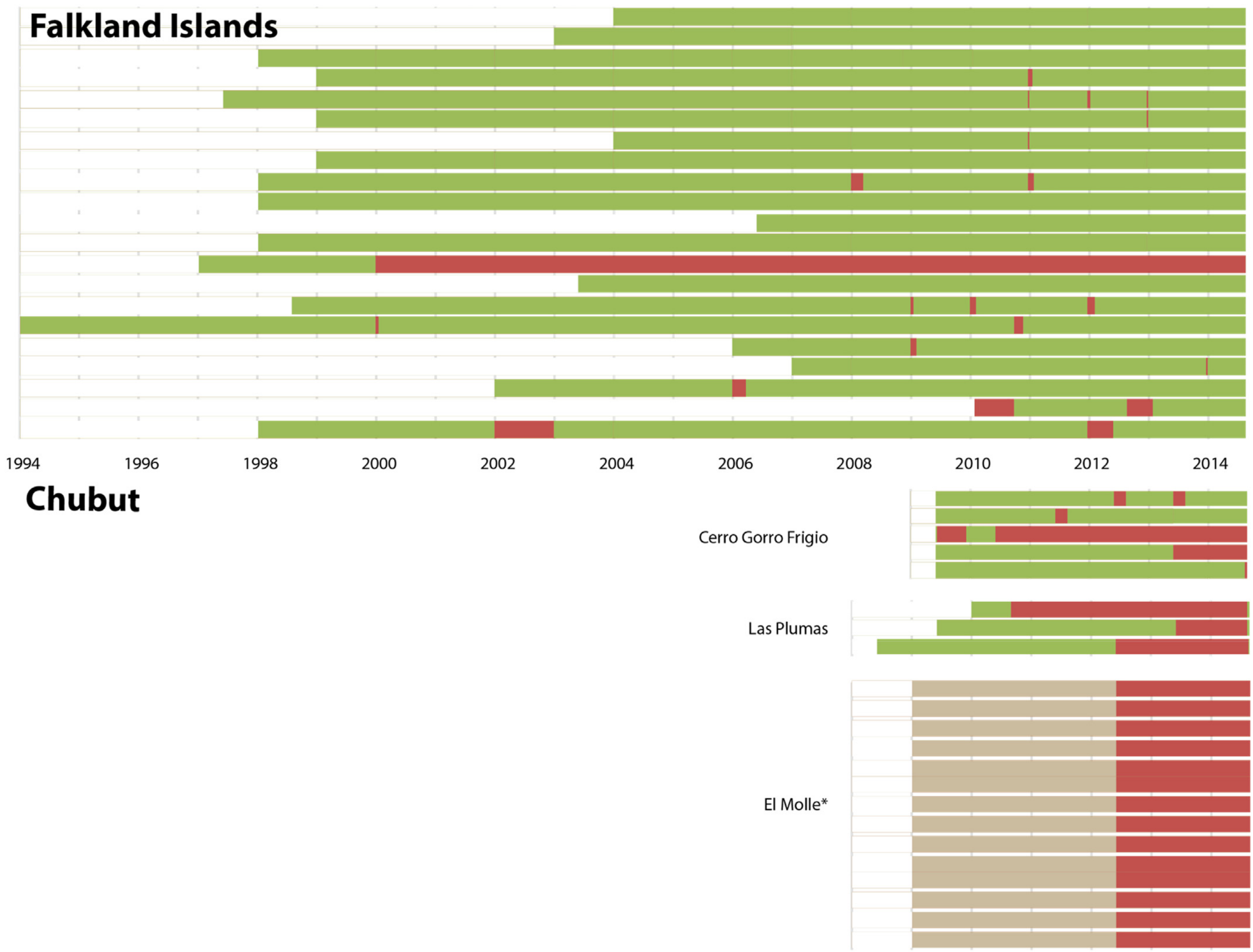

Fig. 8. Uptime timeline showing operational (green) and out of service (red) periods for each HWS visited during this research. Each bar represents the SWT and battery/inverter components of a single HWS, i.e. generators are not represented in this figure. Thus the red part of the bars represents whether the renewable energy system is functioning from the perspective of the user, i.e. are the lights on or not? Users with generators would have to run them whenever they wanted to use power during these periods. * Detailed timeline data was not recorded for the 14 HWS visited in El Molle, however all HWS were reported to be out of order for at least 2 years at the time of the field visit. Prior to this is shown in grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

technical faults that are relatively simple to resolve, or that could have been prevented if regular servicing had been carried out. The lack of integration with existing infrastructure forced wealthier users to abandon their HWS, firing up pre-existing diesel/petrol generating sets to continue using electrical appliances. Less well-off users reverted to gas/kerosene lighting and battery powered radios.

> "Rural people were demanding that the systems worked, because … they really made a difference … they needed somebody to take responsibility for maintenance."
>
> [El Maitén Electricity Cooperative, Chubut, September 2014]

In the Falklands/Malvinas, the 24 h availability of power from battery inverter systems offered new levels of comfort and convenience, particularly thermal comfort. With an SWT, farmers reported saving 60–80% on diesel, however, these cost savings were largely displaced by increased expenditure on kerosene for the upgraded heating systems. Many farmhouses were able to install modern central heating systems with diesel or kerosene burners, as both the burners themselves and the circulating pumps require electricity. In addition to offering a more consistent thermal distribution throughout the living space, they offered significant improvement in indoor air quality and time savings over traditional peat-fired stoves, which require significant manual labour to cut, dry and transport the peat, as well as to maintain the fire.

Whilst Falkland Island/Malvinense farmers had already transitioned to electric shearing equipment (shears and wool press) when Lister generating sets arrived in the 1960s, the flexible wind-diesel 24 h power systems enabled farmhouses to meet this increased energy demand during the shearing period. The 24 h power systems also made a valuable contribution to rural livelihoods by facilitating the diversification into tourism and running low power 24 h loads such as egg incubators or electric fences directly off the main battery bank.

Whilst the HWS in Chubut were more modest in capacity, many of the beneficiaries did not previously have any form of HH electrical generation. Consequently, electric lighting and connectivity with the outside world via the radio were highly valued. In theory, the systems were capable of much more, as each HH system had 12 V DC sockets and connections for an inverter in the main junction box. However, in practice, even among HHs with functional systems, few were observed to be using additional electrical appliances due to the financial, logistical and technical barriers required to source and purchase a suitable inverter or 12 V DC appliances.

The larger systems employed in the Falklands/Malvinas allowed farmers to use almost all appliances, the main limitation being when

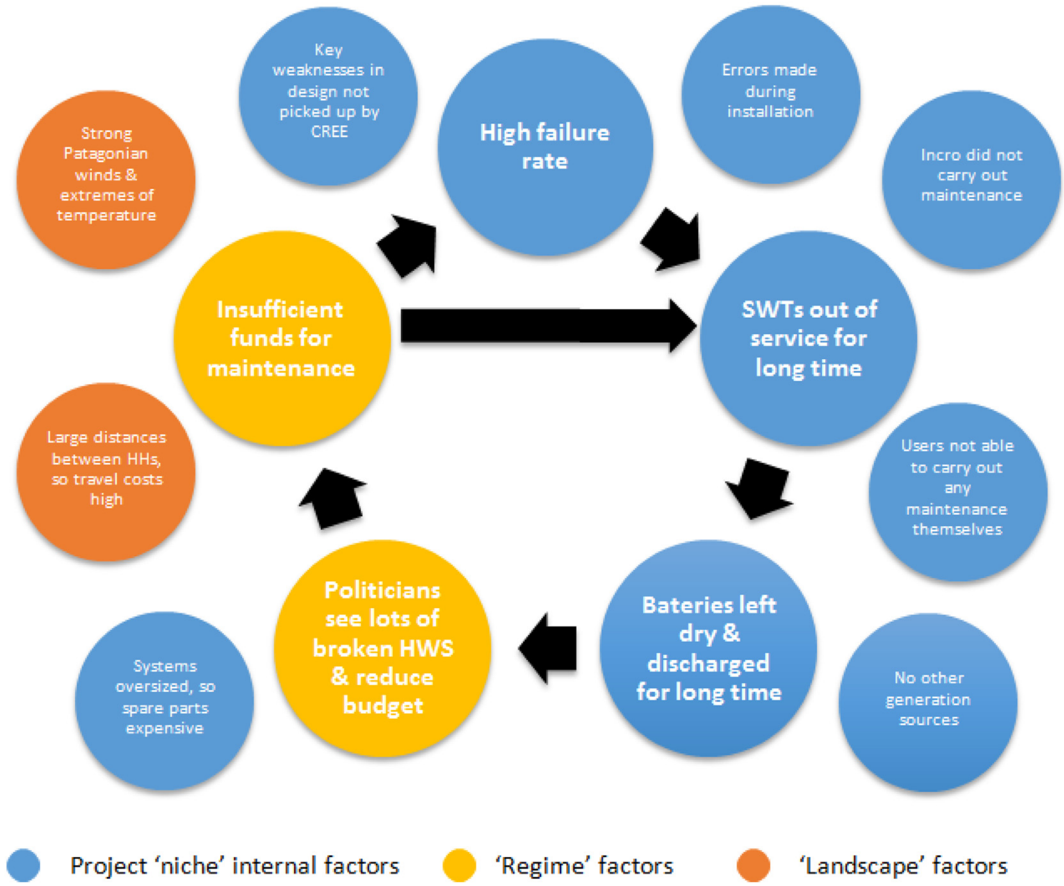

Fig. 9. The vicious cycle leading to the demise of the vast majority of the 1500 HWS installed under the PERMER programme in Chubut, Argentina.

they could use them and for how long. Each system was carefully dimensioned to match the real and evolving needs of each HH, which ensured that the impact of each energy system was maximised for the minimum cost and/or inconvenience to the end user. Each system was initially sized according to actual load profiles measured with a datalogger on the existing diesel generation system. It was subsequently refined though ongoing dialogue between system designers and end users, informed by monitoring data from e-meters, which allowed users to adapt their daily routines to make the most out of the available energy or decide how to expand the system with more generation and/or storage. As a result, each system continuously evolved and was highly valued by its user.

In contrast, no such dialogue occurred in Chubut, so even when functioning properly, the value of the PERMER systems was severely limited. Consequently, although designed for expansion, the vast majority of the standardised systems issued to every HH, regardless of size, livelihood, technical capacity, needs/wants/desires, existing access to energy etc. remained trapped in this initial state, offering electric lights and radio,[15] but little more. As a result, the PERMER systems were vastly oversized for what essentially became an electric lighting system.

As a direct consequence of the failure of the experimental small wind programme in Chubut, subsequent implementations of the PERMER in other Argentine provinces opted for lower capacity Solar Home Systems (SHS), even in the more southerly provinces of Santa Cruz and Tierra del Fuego, where the wind resource is stronger and the solar resource weaker. These systems provide basic energy services (lighting/radio) at a much lower initial purchase cost and with much lower maintenance requirements.

Critical factors

The following section presents a summary of the most critical factors, referring to the appendix for the rich detail of how each individual factor contributed to the successes and failures observed in Chubut and the Falklands/Malvinas. It is structured using the a priori codes from the socio-technical systems (STS) framework: organisational, economic, social, technical and political. A table in each section breaks down the analysis process by showing the a priori codes from both the STS framework and strategic niche management (either internal, resulting from the niche level; or external, resulting from the interaction with the broader regime and landscape levels) assigned to each factor (empirical code). External factors create opportunities or challenges for rural electrification programme designers, whilst internal factors are the results of the decisions they have made when designing the programme. This distinction is important, as it highlights what could have been done differently (i.e. the internal factors). Finally, the factors are categorised into barriers and drivers, as each may be present in one context and absent, or even opposing in the other.

Organisational factors

The results of this research indicate that the centralised model of operation and maintenance chosen by the DGSP in Chubut fell apart when it became trapped in a vicious cycle of decline (Fig. 9). The cycle is characterised primarily by project 'niche' internal organisational failures (e.g. ineffective maintenance network, centralised project coordination resulting in knowledge concentration). However, the inaccurate assessment of the influence that 'landscape' factors (extreme wind conditions

[15] In fact, even the radio was of limited use, as the SWT and the fluorescent tubes both introduced harmonics into the system and as the radio signal in rural areas is often very weak, so even these relatively low levels of interference had such a dramatic effect that users had to brake the wind turbine and turn off the lights to listen to the radio.

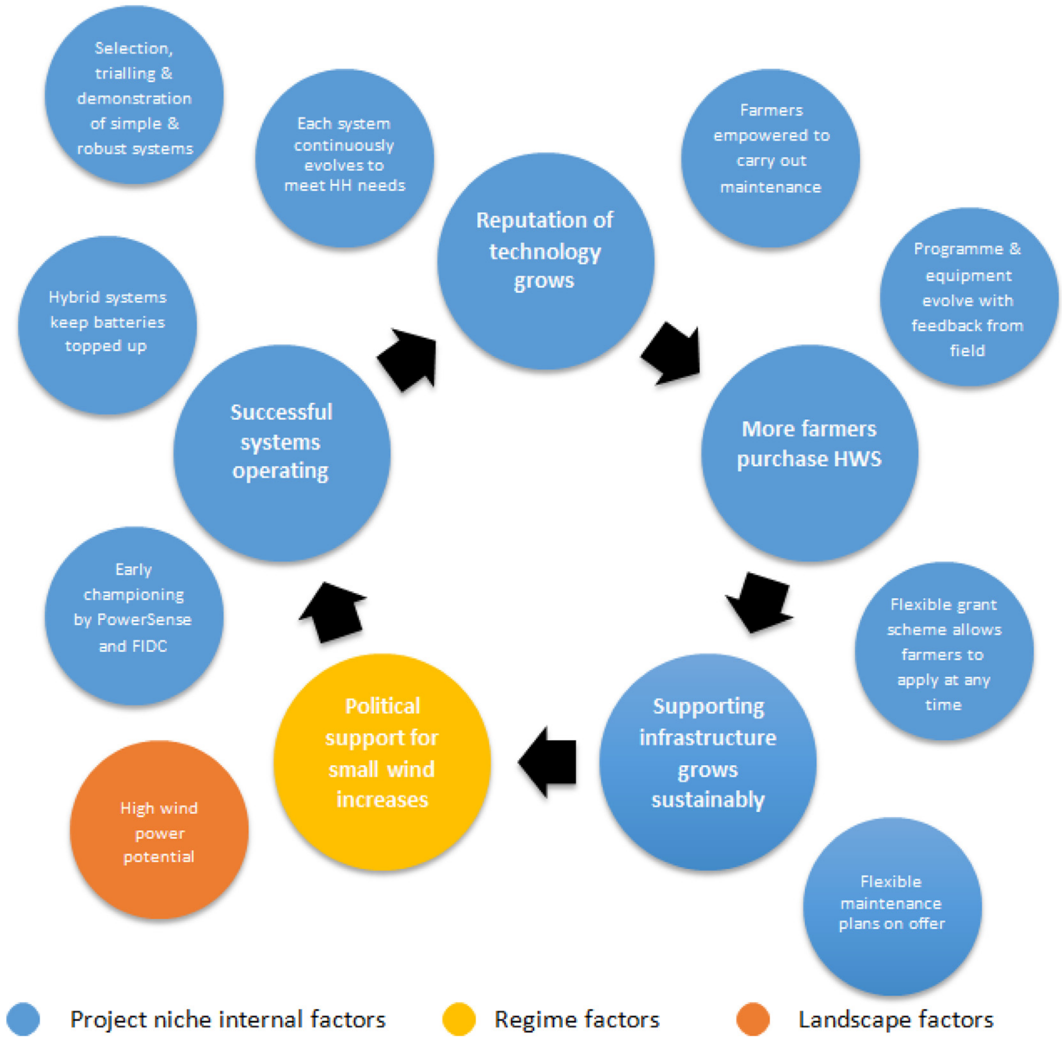

Fig. 10. Positive cycle leading to the successful dissemination of HWS across Falkland Island/Malvinense farms.

and dispersed settlement of end users with poor transportation infrastructure) would have on the time and cost required to implement the project also played a critical role. Both of these mistakes were negatively reinforced by the 'regime' factors (politicians seeing lots of broken HWS and consequently reducing the budget available for maintenance), which prevented the insights gained through learning processes within the 'niche' that could have solved many of the organisational challenges from being carried out.

In the Falklands/Malvinas, the evidence shows that strategy of empowering users to maintain their own equipment, supported by flexible maintenance plans to cater for varying budgets and technical abilities, led to long-term successful operation of the HWSs (see Fig. 10). This highlights the importance of the reciprocal relationship of networking and learning processes along the niche development trajectory. Moreover the results underline the importance of well-designed preliminary studies. The FIDC and PowerSense described a three-step process:

1. wind resource assessments to determine the seasonal variation, synchronicity with solar and actual wind resource at HH sites;
2. power curve verification and durability studies with selected SWTs under local conditions; and
3. market assessments to match HH energy demand with a range of system architectures.

What is more, not only was each HWS tailored to the individual needs of each HH (as described earlier), but the whole programme continued to evolve, meaning that each new system could take advantage of the knowledge aggregated from all previous installations and any new equipment that had recently become available.

Additional organisational factors are summarised below in Table 3 and discussed in detail in Appendix A: Detailed analysis of critical organisational factors.

Economic factors

Maintenance costs for SWTs are high, especially in regions with extreme winds, where wear and tear is greatly accelerated. In Chubut the logistical costs involved in managing a decentralised renewable energy initiative with a centralised maintenance team were so great and the amounts collected by the symbolic user tariffs so small, that when external funding was withdrawn, the programme collapsed. In both contexts, but particularly in the Falklands/Malvinas, generators had already spread widely through market-based mechanisms, as the low initial purchase cost and ongoing fuel cost is much easier for users to accommodate than the high up-front cost structure typical of renewable energy systems. However, the FIDC grant scheme offered farmers a flexible grant funding mechanism to overcome this barrier. End users reported that the resulting diesel savings could be readily diverted to cover HWS maintenance costs, or reinvested in new appliances.

In recent years, the relative price points of SWTs and PV have reversed. Powersense noted that whilst in 1997, the retail price of a

Table 3
Categorisation of key organisational factors using a priori and empirical codes (factors). Each factor is indicated as either a barrier (B) or driver (D) in each context and the most critical factors are **underlined**. A priori codes are derived from socio-technical systems (STS) and strategic niche management (SNM), with the latter defined as internal/external (I/E) to the project niche in each case study.

A priori codes		Critical factor (empirical code)	Consequences	CH	FI	Evidence
STS	SNM					
Organisational	I	Several private companies offering maintenance & upgrade services	**Flexible maintenance plans for sites with varying levels of accessibility & end users with varying budgets & technical abilities**	B	D	CH1,3,8; FK1,3,6
	I		**Spare parts available & affordable**	B	D	CH3,4,11; FK6,5
	E	Small scale (<100 farms)	Simplifies planning, implementation & maintenance	B	D	CH1,3; FK1,2,5
	E	Strong links with UK/USA	Key personnel able to train overseas	B	D	FK1,3,6
	E		Strong supply chain for importing components already in place	B	D	CH5; FK1,3,6
	E	Strong national small wind industry	All components sourced within the country	D	B	CH1,5,7
	I	**Successful early championing by key actors**	**Well targeted feasibility studies & successful piloting pave the way for roll out of larger scale programme**	B	D	CH1,9; FK1,3
	I		**Simple, robust equipment appropriate to local context selected for scale up**	B	D	CH1,9; FK1,3
	I	**Standardisation of equipment**	Interchangeable spare parts & familiarity with key points of failure	D	D	CH1,7; FK3,6
	I		Dependence on a single company for spare parts	B	B	CH1; FK3,6
	I	Private companies in key roles experiencing financial difficulties	**Maintenance services not available during this period**	B	B	CH1,7; FK1,3,6
	I	Installations staggered over long time period	Sustainable development of supporting infrastructure.	B	D	CH9; FK1,2,3
	I		**Key learning points from previous installations inform design of subsequent installations.**	B	D	FK1,3
	I	**Feedback from field to programme designers & manufacturers**	Electrification programme & design of equipment continuously evolves to meet needs of users & overcome context-specific challenges. **Users highly value systems.**	B	D	CH1,4,7; FK1,3,5,6

Table 4
Categorisation of key economic factors using a priori and empirical codes (factors). Each factor is indicated as either a barrier (B) or driver (D) in each context and the most critical factors are **underlined**. A priori codes are derived from socio-technical systems (STS) and strategic niche management (SNM), with the latter defined as internal/external (I/E) to the project niche in each case study.

A priori codes		Empirical code	Consequences	CH	FI	Evidence
STS	SNM					
Economic	E	**Falling cost of solar PV**	PV-wind & PV-diesel hybrids more viable[a]	D&B	D &B	CH5;FK3
	I	Well targeted subsidy	Poorest members of society benefit most	B	D	CH3;FK1
	I	Flexibility in accessing subsidy	HH could apply at a time convenient for them	B	D	FK1,5
	E	Ability to pay	**All HH able to make significant contribution towards initial purchase & ongoing costs**	B	D	FK1,5,6
	I	Private & public sector collaboration	Financing of larger systems	B	D	FK2,6

[a] This is both a barrier and a driver, as it both makes PV-wind hybrid systems more viable (i.e. a driver for HWS), but also makes PV-diesel or PV only systems more viable (i.e. a barrier for HWS).

Proven WT2200[16] could only buy approximately 1.8 kW of PV, in 2012 the upfront cost of a Kingspan 2.5 kW[17] could alternatively be invested in 12 kW of PV.

Additional economic factors are summarised below in Table 4 and discussed in detail in Appendix B: Detailed analysis of critical economic factors.

Social factors

In Chubut, strong rural-urban migration trends have left many communities with a predominantly elderly population, with low levels of formal education. However, it was observed that many of the beneficiaries of the PERMER programme also own wind pumps and/or generators (some even already owned an SWT), which had been purchased on the free market from local suppliers. When it became apparent that the promised two visits per year were not going to happen, most systems were simply left to fall apart, as the lack of basic training and access to technical assistance or spare parts left users powerless to do anything at all. In fact, even the most proactive HH, who also had the resources to purchase spare parts were prevented from doing so, as users were not allowed to climb or lower the tower and the batteries and control system was housed in a padlocked box. Some users even saw the SWT as a foreign object taking up space on their land:

> "The turbine doesn't mean much to me, it's more of an ornament."
> [Chubutense farmer & PERMER-Chubut beneficiary, September 2014.]

In contrast in the Falklands/Malvinas, a high sense of ownership was observed, as farmers were empowered to maintain their own equipment, whereas in Chubut, the state remained the owner of the systems. The fact that farmers had to actively make the decision to invest significant amounts of their own money in the equipment was found to be extremely important in establishing ownership. As a result, the majority of HHs were willing to adapt their daily practices around the availability of renewable resources: "*you look out the window & if that turbine's going round something wicked, you stick the electric kettle on!" (Falkland Island farmer & FIDC Beneficiary, August 2014)*. What is more, the higher level of education and mechanisation of farms in the Falklands/Malvinas offered a much stronger base on which to establish a sustainable rural

[16] Approximately £4000 ($10,487 in 2008 USD).
[17] The Proven WT2200 was first upgraded to the Proven WT2500 in the late 90s, which then became the Kingspan 2.5 kW. In 2012, the SWT alone sold for £7000 ($12,511 in 2008 USD).

Table 5
Categorisation of key social factors using a priori and empirical codes (factors). Each factor is indicated as either a barrier (B) or driver (D) in each context and the most critical factors are **underlined**. A priori codes are derived from socio-technical systems (STS) and strategic niche management (SNM), with the latter defined as internal/external (I/E) to the project niche in each case study.

A priori codes		Empirical code	Consequences	CH	FI	Evidence
STS	SNM					
Social	I	**Integrating maintenance practices with local culture**	Majority of preventative maintenance practices successfully carried out by end users	B	D	CH3;FK3
	E	End user levels of education high	**Users generally have thorough understanding of their HWS & are willing to adapt daily routine around availability of renewable resources**	B	D	CH3,9;FK5
	E	Wind power historically used for power generation	Technical capacity & awareness of wind power already high	D	D	CH12,4; FK3,5,6
	I	Ownership of systems	**End-users more/less determined to take care of equipment & resolve problems independently**	B	D	CH3,7,9; FK5
	E	Many sites too remote for grid connection	Small-scale off-grid systems only practical solution for many HH	D	D	CH3,4,9; FK1,2,3,5
	E		**Travel time/cost to each HH high**	B	B	CH1,3,7,8; FK3,6
	I	Low tilt-up towers, simple equipment & basic user training	**Users empowered to carry out majority of preventative maintenance themselves**	B	D	CH1,3,7,11
	E	Wind power successful at multiple scales & for many applications	Capacity building, awareness raising and political support for wind power increases	B	D	CH4,12; FK1,2,4
	I		Each system sized appropriately for user/s needs	B	D	CH3,9; FK3,5,6
	I		**Existing/new livelihoods enhanced/created**	B	D	CH3;FK1,5

electrification programme. Many farmers reported that they already had many of the tools needed to repair a SWT and were very capable at repairing heavy machinery, such as off-road vehicles.

Additional social factors are summarised below in Table 5 and discussed in detail in Appendix C: Detailed analysis of critical social factors.

Technical factors

In Chubut, the research team observed that in most cases the battery bank, which was kept in a locked container, had completely failed. Many interviewees pointed out that no maintenance was carried out on the batteries by DGSP, most critically, topping up the electrolyte, which must be done every few months or the cells dry out and quickly degrade. Another recurrent topic among the interviewees was the complete discharge of the batteries due to the technical failure of their SWT, which decreased their lifetime even further. Many end users and other stakeholders reported that the design of the Eolux SWT was not adequate for the harsh Patagonian winds. The root cause of many of the SWT failures observed by the research team during field visits in Chubut can be attributed to the Eolux G2 A500's reliance on a single poorly designed and manually operated friction brake.

In most other contexts, a full wind resource assessment requiring an anemometer installed on a meteorological mast at hub height for at least one year is recommended; however, a simple on-site inspection to locate the SWT upwind of any significant obstacles generally suffices in both the contexts under study. In fact, sites with extremely high winds were found to pose more of a risk than the lack of wind resource, especially for the Eolux in Chubut, as it only needs the user to forget to apply the brake during a storm once and the SWT will be destroyed.

In the Falklands/Malvinas, many components exceeded their expected lifetime, as simple yet robust equipment that is appropriate for high wind sites was carefully selected by programme designers. Moreover, the interviewees reported that regular maintenance check-ups were able to prevent minor failures from becoming catastrophic disasters. Critically, the Proven/Kingspan SWTs used in the Falkland Islands use 6 m tilt-up towers that can be lowered by anybody with an off-road vehicle, empowering end-users to carry out basic maintenance themselves.

Whilst hybridisation with PV was not a viable option several decades ago, dramatic cost reductions mean that it now has an important role to play. In both contexts, the wind resource is relatively steady throughout the year (see Fig. 11), whilst the solar resource is low in winter (<2 kWh/m^2/day). However the Falklands/Malvinas' higher latitude and greater rainfall (800 mm/yr), as well as Chubut's Andean region (700–3000 mm/yr), reduce the solar resource even further (Cotter, 1999; MEM, 2015). However, even in these near ideal contexts, the temporal variability in the wind resource is still extremely high, suggesting that hybrid systems can offer significant value: *"Even here, there are days*

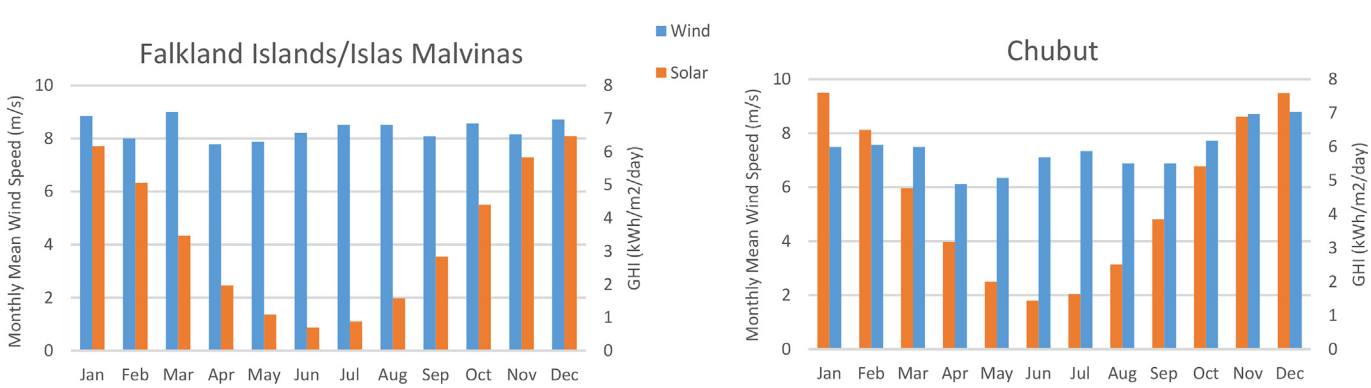

Fig. 11. Seasonal variation in wind and solar resources in the Falklands/Malvinas and Chubut. Falklands/Malvinas wind data measured at 10 m height from October 2002 to October 2003 by Tim Cotter of FIDC for Sand Bay wind farm resource assessment. Solar data downloaded from NASA (2014) satellite measurement data set.

Table 6
Categorisation of key technical factors using a priori and empirical codes (factors). Each factor is indicated as either a barrier (B) or driver (D) in each context and the most critical factors are **underlined**. A priori codes are derived from socio-technical systems (STS) and strategic niche management (SNM), with the latter defined as internal/external (I/E) to the project niche in each case study.

A priori codes		Empirical code	Consequences	CH	FI	Evidence
STS	SNM					
Technical	E	High winds & low vegetation across entire territory	**Individual site assessments not necessary**	B	D	CH1;FK1,2,5
	E		**Extreme winds destroying all but the most robust turbines**	B	B	CH2,3,5; FK1,2,5,6
	E	Low solar resource in winter & few viable micro-hydro sites	**Choice restricted to wind before recent global PV price drop**	D	D	CH4,10; FK1,3,5
	E	Solar and wind resources both peak in summer	PV-wind hybrids less viable	B	B	CH10;FK1
	E	Highly saline coastal environment	Galvanised parts necessary	D	B	FK1,3
	E	Extremes of temperature	Batteries stored outside have shorter life	B	D	CH3,5
	E	No hurricanes, typhoons or tornados & few lighting strikes	Fewer failures	D	D	
	I	**Hybrid systems**	Diversity in power generation sources offers greater continuity of supply to keep batteries topped up	B	D	CH3;FK3,5
	E	All farms had generators	Able to build upon existing infrastructure & design RE systems to addresses weaknesses of generators	B	D	CH3;FK1,3,5
	E	SWTs have moving parts	Maintenance requirements of SWTs higher than PV	B	B	CH3,5,9; FK3,5,6
	E		SWTs have similar maintenance requirements to generators if preventative maintenance carried out	B	D	FK5

without any wind at all" Falkland Island farmer & FIDC beneficiary, August 2014. The diesel generators in the Falklands/Malvinas offer a dispatchable power supply and can therefore cover both calm days and periods when the SWT is out of service. PV may not be dispatchable, but the probability of failure is so low that they offer a valuable trickle of energy that is able to top up the batteries when other less reliable power generation sources are out of service.

Additional technical factors are summarised below in Table 6 and discussed in detail in *Appendix D: Detailed analysis of critical technical factors.*

Political factors

In both regions, sovereignty disputes have precipitated national policies supporting the settlement of rural areas and as a result, political support for local residents continue to the present day in the form of state subsidies and infrastructure development. However, compared to the sporadic nature of political support for the PERMER programme in Chubut, the strong and consistent institutional support from FIG and FIDC offered a relatively stable environment for HWS to permeate throughout rural society at a sustainable rate. The interviewees reported that each new successful installation built capacity, raised awareness and boosted political support. Official government endorsement gave end users confidence in technology choice and the willingness of these two institutions to work with local enterprises, such as PowerSense and SURE, to overcome the key barriers that small wind faced in the Falklands/Malvinas was absolutely critical in building a sustainable rural electrification programme.

Despite the large number of failures seen in Chubut, Eolux is considered to be one of the most reliable machines available on the Argentine market. However, on the socio-technical 'regime' level during the time of the research, the market was protected from overseas competition by high import taxes and long delays in customs. The lack of choice of reliable equipment for extreme conditions in Argentina can be partly attributed to the limited size of the domestic market (to which manufacturers are largely confined to due to the inability to compete in markets with unrestricted imports).

Additional political factors are summarised below in Table 7 and discussed in detail in Appendix E: Detailed analysis of critical political factors.

Discussion

The insights in the following sections are featured in the briefing paper: "*Is there still a role for small wind in rural electrification programmes?*" (Leary et al., 2018), which although published first, was written alongside this paper.

This study aimed to provide insights into and recommendations for the development and diffusion of HWS in remote high wind regions using socio-technical transitions theory. The factors influencing the long-term sustainability of these systems are an interplay of technological, organisational, economic, political, and social factors, as well as both internal factors resulting from the 'niche' level and external factors from the 'regime' and 'landscape' levels. Numerous studies have shown that MLP's heuristic nature is a major strength, which allows it to deal with complex, multi-dimensional and dynamic phenomena (Best,

Table 7
Categorisation of key political factors using a priori and empirical codes (factors). Each factor is indicated as either a barrier (B) or driver (D) in each context and the most critical factors are **underlined**. A priori codes are derived from socio-technical systems (STS) and strategic niche management (SNM), with the latter defined as internal/external (I/E) to the project niche in each case study.

A priori codes		Empirical code	Consequences	CH	FI	Evidence
STS	SNM					
Political	E	Need to keep rural areas populated to demonstrate sovereignty	Political support for rural livelihoods	D	D	CH4,9;FK3
	I	**Strong & consistent institutional support for HWS programme**	Ability to systematically identify & overcome context-specific barriers	B	D	CH1,5,10; FK1,2,3
	I		Development of local capacity for system design, installation, operation & maintenance	B	D	CH8;FK1,2,3
	E	**Political support for local manufacture**	Development of a local small wind manufacturing industry	D	B	CH4,5

Prantner, & Augenstein, 2012; Geels, 2002, 2012; Geels et al., 2016; Raven, 2006; Verbong & Geels, 2007). However, during this study the authors found it challenging to operationalize the concept – whilst the 'landscape' and 'niche' levels were easier to define, each researcher started with a different interpretation of where the 'regime' level fitted. "What actually is 'the regime' to be researched and possibly managed, is not given some kind of clear system boundaries but is a matter of framing and deliberation" (Geels, 2011; Holtz et al., 2008). In contrast, SNM was considerably easier to operationalize and offered valuable insides into the dynamics between the local and global level of the niche development and its internal dynamics.

These case studies illustrate the importance of developing the organisational 'niche' level around the context specific 'landscape' factors. Most critically, although Argentina's extensive territory offers a diverse natural potential for renewables, it also creates challenges for the provision of maintenance services across such a broad geographical expanse. Both case studies indicate that a resilient and accessible decentralised maintenance network is absolutely essential in contexts with dispersed settlement patterns, where high failure rates from extreme wind conditions are expected. High winds offer high energy yields, but also greatly increase wear on SWTs, meaning that only the most robust machines survive. The lower initial purchase costs of less robust machines can lure rural electrification programme designers into a false economy, as maintenance costs can quickly spiral out of control after the first big storm hits. Moreover, the Chubut shows that once the reputation of the technology is damaged, it can be very difficult to change perceptions. Furthermore, both cases have shown that in projects dependent on external funding, strong and consistent support from the political 'regime' level is crucial to foster the sustainable growth of a small wind power ecosystem.

Comparing these two cases showed that small wind electrification programmes must be planned with maintenance as the core priority. Rural people have to be resourceful, as regularly calling out a specialist from the city is impractical. Users should be empowered to carry out as much maintenance as they are able and willing to through ownership of the equipment, basic training and the support of a strong and accessible service network. Decentralised energy systems require a decentralised maintenance network, which build upon existing organisations, with established links to rural people and relevant technical capacity. Further research should be undertaken to develop and pilot possible solutions for the 1000+ HHs with broken HWS in Chubut. Partnering with local telecoms/power cooperatives and empowering end-users through participatory SWT construction programmes in technical schools are two particularly promising strategies.

Hybrid systems offer significant value, as SWTs are notoriously unreliable and even in high wind regions, the wind resource is still extremely variable (in both space and time). The battery bank is the most expensive component in a HWS - ensuring a steady trickle of current flows in every day can greatly increase its lifetime. Generators can top up at any time and meet short term peaks in demand. Many HHs already have access to a generator, so HWS should build upon this existing infrastructure, rather than attempting to totally replace it. PV is modular, easy to install, operate and maintain - even in regions of low solar resource the price of PV is now so low that it should be included in every system. In fact, globally speaking, in most cases, PV-diesel systems are now the least cost option, even before adding the disproportionately higher maintenance costs of SWTs into the equation.

Local champions have a vital role to play in establishing their local HWS 'niche' by adapting generic wind power knowledge by identifying and tackling context-specific barriers. Firstly, with well targeted feasibility studies, then piloting appropriately selected equipment, establishing a decentralised maintenance network and finally creating effective feedback loops from the field to programme designers and equipment manufacturers. The installation of a HWS is only the first step in a long journey towards creating sustainable energy infrastructure in an off-grid region. Technical support and spare parts be available for when things break (or to prevent them breaking) and each system must continually evolve to meet the needs of its user/s. Local champions should advise users on upgrading hardware and adapting their practices to optimise their system. Users must be comfortable approaching them for advice and they must be intimately familiar with rural life, so that their advice is compatible with local practices.

Although standardisation of system components can significantly streamline manufacture, installation and maintenance,[18] the one-size-fits-all approach is incompatible with the diversity seen in HHs across any region. The extreme variability in the wind resource and the high maintenance requirements of SWTs mean that even in high wind regions, HWS are not appropriate for all HHs. To address this, preliminary market assessments should aim to categorise HHs within the target region and match them with a series of tried and tested system architectures. For example, 100 W-scale solar systems for very remote HHs with low technical capacity and low demand, 1 kW scale PV-wind-diesel hybrids for larger, more accessible and technically capable HHs with good wind resource, etc. The following key factors should be assessed:

- HH size;
- key livelihoods;
- priority energy services and intended patterns of use;
- ability/willingness to pay for initial/ongoing costs;
- ease of integration with existing energy infrastructure (e.g. generators);
- ease of access to existing/proposed maintenance networks (both physically and via telecommunications);
- willingness/ability to carry out maintenance;
- locally available wind & other renewable resources:
  - o excessively windy/turbulent sites significantly increase maintenance requirements; and
  - o low wind sites offer uncompetitive energy yields.

Conclusion

This paper compared small wind rural electrification initiatives in two of the world's windiest regions, with the aim of drawing out the critical success factors to inform practitioners and policy makers developing similar such initiatives in other remote, high wind regions. In Chubut, Argentina, 1500 HWS installed under the PERMER programme soon fell into disrepair as the centralised system for maintaining this remote decentralised infrastructure fell apart when state funding was withdrawn. In the Falkland Islands/Islas Malvinas, long-term institutional support from the FIDC enabled the sustainable growth of a small wind ecosystem, firmly embedding a strong decentralised maintenance network within rural society.

The key learning points for future small wind rural electrification programmes in other remote high wind regions[19] were found to be:

- Hybrid systems mitigate the highly variable wind resource and unreliability of SWTs.
- Continually review PV and SWTs prices and properly account for maintenance costs.
- Empower end users to carry out as much maintenance as possible by:
  - o developing ownership;
  - o integrating maintenance practices with local culture; and
  - o establishing a decentralised maintenance network.
- Create effective feedback loops from the field to programme designers/equipment manufacturers.
- Invest in robust equipment that can survive extreme winds.

[18] Simplifying the supply chain for spare parts and allowing users and technicians to become familiar with common failures and their remedies.

[19] See Fig. 1 to identify regions with wind regimes comparable to Chubut and the Falkland Islands/Islas Malvinas.

- Determine whether an SWT is right for each HH's unique and evolving needs/preferences.

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Appendix A. Detailed analysis of critical organisational factors

In Chubut, the misjudgment of the effect that 'landscape' factors would have on the project, led to higher than expected failure rates in the strong and cold Patagonian winds. As a consequence, after spending significant time and effort travelling to very remote sites across the province to carry out an initial round of repairs, the Incro maintenance team simply abandoned the project, leaving many machines out of service. A recurrent theme emerging from the end user interviews was that since the state was designated as responsible for maintenance, end users had received no training and had no direct access to spare parts. In theory, they could call the DGSP in Rawson at any time, however even those that did were extremely unlikely to ever see a technician, as the funding for the project dried up due to the bad reputation that it had gained. Many key stakeholders reported that the cycle was triggered by the failure of the local company, Incro, who had been contracted to carry out two visits per year to each of the 1500 state-owned decentralised power systems scattered across the province, but had recently fallen into financial difficulties.

The project team members within the DGSP reported that the key decision makers on the political 'regime' level who heard about the project diverted the province's scarce public services budget to larger settlements, where the cost of providing basic services per HH is much lower. At the same time, it was reported that the project's internal problems increased as the bill for repairs began to increase exponentially, as even minor failures began to quickly spiral out of control (see *Appendix D: Detailed analysis of critical technical* below). Due to excessively bureaucratic internal processes, the termination of the maintenance contract with Incro dragged on for many years and by the time the DGSP formally took over maintenance of the systems, the majority were in a state of disrepair and the resources to carry out much needed repairs were scarce. Although some initial efforts were made to establish a maintenance network, the lack of funding prevented trained personnel from carrying out their roles, as they had no transportation, tools or spare parts.[20] As a result, only the DGSP team in Rawson were able to carry out maintenance, yet the costs for sending trained personnel out across this huge province are enormous. Consequently, even simple repairs have a prohibitively high cost:

> "maintaining 1,500 systems spread out across the entire of the province with a team based in Rawson is impossible."
> [El Maitén Electricity Cooperative, Chubut. September 2014]

The interview transcripts with the DGSP's project manager revealed self-critical reflections on the real needs of the end users and whether the delivery model originally conceived for the project was capable of meeting these. This shows that the second-order learning processes (Grin, Rotmans, Schot, Geels, & Loorbach, 2010; Hoogma, 2002; Urban & Nordensvärd, 2013) required to aggregate knowledge from the field and effectively develop viable pathways to break free from the vicious cycle were occurring. In fact, several of these pathways had already been explored. For example, the DGSP formed allegiances with rural electric/telecommunications cooperatives across the province. As service providers in remote regions where private companies are unable to operate profitably, partnering with the cooperatives offered the opportunity to vastly reduce transportation costs and leverage their existing technical capacity and personal relationships. The project manager highlighted that the cooperatives have personal motivation to care for their membership, enhancing the programme's social impact by prioritising maintenance for the most vulnerable. At the time of the field visits, the El Maitén cooperative visited by the researchers had managed to successfully repair many of the 413 PERMER HWS in their local area, however this attempt to decentralize the provision of maintenance services was still held back by the lack of centralised funding.[21] It was also suggested by several informants that not all cooperatives would be strong enough to take on all maintenance responsibilities in the same way as El Maitén had, even if sufficient financial resources had been made available.

The general picture emerging from the analysis of the Falklands/Malvinas case is that the strategy of empowering users to maintain their own equipment, supported by flexible maintenance plans to cater for varying budgets and technical abilities, was far more sustainable.

In the Falklands/Malvinas, early championing from Clive Wilkinson at PowerSense and Tim Cotter at the FIDC was critical in establishing the niche for HWS. Close ties with the UK and USA enabled key personnel to train overseas and acquire the skills required to design, test, install and maintain renewable energy systems.[22] It is widely acknowledged across the islands that the long-term commitment of these two pioneers *"got wind power up and going in the Falklands" (Falkland Island farmer & FIDC Beneficiary, August 2014)*. This highlights the importance of the reciprocal relationship of networking and learning processes along the niche development trajectory.

Initial feasibility studies were carried out by the FIDC in the Falklands/Malvinas and by CREE in Chubut (power curve verification and wind resource/market assessments). In the Falklands/Malvinas, well-designed preliminary studies and piloting paved the way for the roll out of the FIDC grant scheme. Experienced renewable energy consultants, IT Power, assisted the FIDC with an initial feasibility study in

[20] Although the DGSP technician visited by researchers in Tecka received a salary, he could only make occasional visits on horseback to the HWS in his local area, and was only able to fix the simplest of faults, as the DGSP was unable to provide him with the necessary resources (pickup truck, tools and spare parts).

[21] As no payment was being collected from users and even a year after officially taking over responsibility for these systems, the cooperative had still received only a handful of spare parts and none of the promised financial support from the DGSP, their actions were grinding to a halt.

[22] Clive Wilkinson of Powersense spent 6 months shadowing renewable energy guru Bubo Schulz on the West Coast of North America and Tim Cotter of FIDC completed the Renewable Energy MSc programme at Loughborough University in the UK.

1994, illustrating the potential for four alternative systems: optimising diesel generation (e.g. smaller generator on at night), demand reduction (e.g. energy efficient appliances) and/or battery inverter system for 24 h power with additional renewable generation. The FIDC carried out wind resource assessments to determine the seasonal variation, synchronicity with solar and actual wind resource at HH sites, then carried out power curve verification studies on Proven wind turbines, which Powersense had shown to be suitably robust with the initial piloting described in the introductory section. Only after seeing positive results at each stage did the programme move forward.

However, in Chubut, the whole process had to be accelerated and constrained due to the conditions of the World Bank administered GEF grant. Consequently, identical systems were issued to users all in one go. As a result, many end users reported that the systems were not well matched with their priorities and that only those whose homes were accessible enough for the initial evaluation team to get to and who happened to be at home when they visited were able to participate in the programme. Therefore, some of the poorest and most isolated members of society were completely excluded.

It was indicated by several key stakeholders that the sudden demand for so many identical systems meant that the capacities of the implementing organisations, particularly the installer, Incro, were overstretched. Consequently, installation errors contributed significantly to the high failure rate that kicked off the vicious cycle of decline:

> "…at the very beginning, we discussed whether we could realistically install 1,500 systems almost instantaneously…but of course… when an opportunity for funding comes up, you have to take advantage of it."
>
> [CREE, Chubut, September 2014]

In contrast, Falkland Island/Malvinense farmers could apply to the FIDC grant scheme at any time and in two phases: battery/inverter 24 h power system, then SWT. Each system was tailored to the individual needs of each HH, but importantly, each new system could take advantage of the knowledge aggregated from all previous installations and any new equipment that had recently become available (later systems were much more likely to include significant PV penetration, taking advantage of the drop in global market prices). Furthermore, organisational capacity among local suppliers and installers grew sustainably, creating the positive cycle summarised in Fig. 10.

Several key stakeholders reported that in Chubut the equipment was selected primarily for its power performance and low initial purchase cost, whilst in the Falklands/Malvinas, the emphasis was on finding robust equipment that would survive the harsh conditions. The Eolux SWTs selected in Chubut were optimised for the less challenging conditions in Northern Argentina and no design modifications were made for the extreme temperatures and wind speeds found in the South.[23]

Although both Argentina and the UK have strong small wind industries, both Chubut and the Falklands/Malvinas are remote regions with limited manufacturing capabilities,[24] where establishing strong supply chains for spare parts and effective feedback loops from the field to the manufacturer are critical. In the Falklands, the FIDC and Powersense carried out many evaluative studies, collected data from e-meters[25] and regularly conversed with users to see how each HH was actually using their system. This allowed them to offer tailored advice to facilitate the continual evolution of each HWS by optimising user practices and/or upgrading hardware, as well as informing the design of future HWS.

However, the population of the Falklands/Malvinas is under one hundredth of the population of Chubut, meaning that it is simply not possible for any one person to become intimately familiar with every single system. Consequently, the DGSP developed a dedicated software package (SIAP[26]) to manage the immense volume of information. However, although a detailed record existed for each system, it was fundamentally limited by the quality of the information that the DGSP received. As they were rarely able to actually visit installations due to their highly restricted budget, the records were predominantly based upon phone calls made by users requesting repairs. However, after receiving no assistance in response to previous requests, many users simply gave up reporting failures.[27] What is more, the difference in socio-economic status between rural people and official government representatives in the administrative capital and the lack of access to telephones in rural areas also created significant barriers that prevented many from calling at all.

> "…people who live in the countryside, many of them, simply don't have basic management skills, the things that we do in the city, that seem so simple to us – I go there, I make a phone call, I get the support I need… for many of them, making a claim is unfathomably complicated."
>
> [CREE, Chubut, September 2014]

In the Falklands, Clive Wilkinson of PowerSense is a farmer himself and as a result, other farmers felt comfortable calling him up and asking for advice, which he could offer in terms that they could relate to. For example, checking the battery fluid levels on "dog dosing day" - once every 6 weeks, reminders are broadcast on local radio and all dogs on the islands are given medication to protect them from a parasitic disease affecting sheep. Remembering to top up fluid levels regularly enabled batteries to last well over 10 and sometimes over 20 years! In contrast, in Chubut, the batteries were locked away in a sealed cabinet. When it became clear that the maintenance team were not able to visit, users that could be contacted by phone were told to cut off the padlocks with a bolt cutter and top up the battery fluid.

As a direct consequence of this lack of information, Giacobone, the manufacturer of Eolux, was unaware of the scale and severity of the problems and the DGSP were left to come up with innovative solutions to the failures they were seeing in the field themselves[28] (see Appendix D: Detailed analysis of critical technical below). In contrast, Proven highly valued the regular feedback they received from PowerSense, as the extreme conditions of the Falklands/Malvinas context enabled their machines to receive rigorous testing in a very short period of time. This symbiotic relationship enabled Proven to create a robust machine that they could market as capable of *"surviving the Falkland Islands"* (Powersense, Falkland Islands, August 2014).

However, this dependency on a single private company based thousands of kilometres away jeopardised the entire programme when Proven went into receivership in 2011.[29] Proven was eventually bought out by Kingspan, but during this process it was understandably very difficult to obtain spare parts and the future of the machines installed on the Falklands was uncertain. To mitigate this issue, FIDC now ensure that a significant stock of spare parts is now kept on the islands.

[23] In fact, robustness was specified by PERMER representatives, however, insufficient testing was carried out by CREE and key weaknesses in the design were not picked up, leading to an excessively high number of failures in the field.

[24] In fact, Chubut does have a small wind manufacturer, TecnoTrol, however the conditions of the World Bank/GEF grant required the state to accept the lowest price offer, even though they were aware that this would create a very long supply chain.

[25] Simple dataloggers measuring key statistics, such as deepest discharge, total number of discharges below 10%, average discharge.

[26] *Sistema Integrado para la Administración del Proceso "suministro de energía eléctrica al poblador rural disperso de la Provincia del Chubut"* - Integrated System for the Administration of the "electricity supply to rural people in the Province of Chubut" Process.

[27] On several occasions the out-of-service HWS visited by the researchers were recorded in the SIAP with only minor faults.

[28] However, as the DGSP does not have production capacity, at the time of writing it was still not able to implement these solutions in the field.

[29] The company had refocused on the emerging UK grid-connected market and redesigned the machines to offer shorter payback periods on what are usually lower wind sites. However, this cost-cutting was at the extent of durability: "In 2008, we had one of the new configurations that lasted 24 h. It just so happened that we put it up, it blew a hoolie and that was it. No more!" (SURE, Falkland Islands, August 2014).

Appendix B. Detailed analysis of critical economic factors

In recent years, the relative price points of SWTs and PV have reversed. Whilst in 1997, the retail price of a Proven WT2200[30] could only buy approximately 1.8 kW of PV, in 2012 the upfront cost of a Kingspan 2.5 kW[31] could alternatively be invested in 12 kW of PV. Consequently, despite the low solar resource in winter, John McLeod at Elephant Beach on East Falkland reports spending less on diesel than his neighbour, several years after reinvesting the funds from selling his Proven/Kingspan SWT back to SURE for spares in a 6 kW PV array. Whilst the energy demand and diesel generation systems are different at each house in the Falklands/Malvinas, four years of measured data now shows that both the 6 kW PV array at Elephant Beach and the standard 2.5 kW SWT both produce around 6000 kWh/yr. What is more, the PV array itself will have virtually no maintenance costs in over 20 years, whilst SURE currently charge £350 per year to service a HWS. However, it should be noted that the majority of this 6000 kWh arrives in the summer, whilst the wind is more evenly distributed throughout the year.

In both contexts, but particularly in the Falklands, generators had already spread widely through market-based mechanisms, as the low initial purchase cost and ongoing fuel cost is much easier for users to accommodate than the high upfront cost structure typical of renewable energy systems. The FIDC grant scheme offered farmers a flexible mechanism to overcome this barrier and there was an existing expenditure (diesel) that could be readily diverted to cover maintenance costs. Further fuel savings could then be reinvested at each farmer's discretion in new appliances, system upgrades or whatever they felt they needed/wanted. What is more, farms were also able to increase their income with access to new and improved productive activities (e.g. egg incubation, electric sheering equipment, tourism). The conditions of the grant ensured that it was well targeted to benefit sheep farmers, by issuing it directly to end users in order to prevent vendors from swallowing it up into their profit margins.

In contrast, although the PERMER programme also attempted to address the lack of financing options, existing expenditures on kerosene, candles, dry cell batteries and propane in Chubut were thought to be insufficient to make a significant contribution towards the ongoing costs of the system. As a result, a token amount was proposed for the user tariffs and when external funding was withdrawn, the programme collapsed. The logistical costs involved in managing a decentralised renewable energy initiative with a centralised maintenance team are so great that it was even suggested by one respondent that it would have been more cost-effective to directly subsidise diesel for isolated HHs. Whilst many rural Chubutenses clearly have significantly lower financial resources than the average Falkland Islander/Malvinense, the province contains a broad socio-economic spectrum that could not be taken into account due to the conditions of the World Bank/GEF grant, which stated that all systems had to be identical. Consequently, no mechanism was created to allow users who could have made a meaningful contribution to the ongoing costs of the system though greater regular maintenance payments or directly purchasing spare parts, to do so.

Appendix C. Detailed analysis of critical social factors

In both contexts, wind has historically been used for power generation, establishing a basic level of awareness and technical capacity. However, the higher level of education and mechanisation of farms in the Falklands/Malvinas offered a much stronger base on which to establish a sustainable rural electrification programme. Most farms already have many of the tools needed to repair a SWT (a Land Rover to lower the tower and a workshop full of power tools) and most farmers are already very capable at repairing heavy machinery, such as Land Rovers. In Chubut, strong rural-urban migration trends have left many communities with a predominantly elderly population, with low levels of formal education. However, it was observed that many of the beneficiaries of the PERMER programme also own wind pumps and/or generators (some even already owned an SWT), which had been purchased on the free market from local suppliers. Whilst the technical capacity and finances of many rural Chubutenses is limited, many others are clearly more than capable of purchasing, installing, operating and maintaining small scale power generation equipment with the assistance of local suppliers/installers/technicians.

In the Falklands/Malvinas, farmers were empowered to maintain their own equipment, whereas in Chubut, the state remained the owner of the systems and was responsible for maintaining them. In the Falklands, particularly capable and motivated farmers could choose to carry out all maintenance themselves, whilst those at the opposite end of the spectrum could pay a private company to take care of everything. This strategy of empowering farmers has been particularly important in building a sense of ownership of the equipment, as Falkland Island/Malvinense farmers would proactively seek out solutions to ensure their systems kept running. In Chubut, when it became apparent that the promised two visits per year were not going to happen, most systems were simply left to fall apart, as the lack of basic training and access to technical assistance or spare parts left users powerless to do anything at all. In fact, even the most proactive HH, who also had the resources to purchase spare parts were prevented from doing so, as users were not allowed to climb or lower the tower and the batteries and control system was housed in a padlocked box. During the field visits, one user who was repairing their car when the researchers arrived explained that they had waited 6 months for engineers to fit a new spring to release the jammed braking system on their SWT. Given the array of tools and their technical competency, it was clear that this repair could easily have been carried out by the user if they had been empowered to do so.

An independent initiative based upon the empowerment of end users was launched in 2014 at the agro-technical school in Cholila, Chubut. The aim of the school is to equip students with the tools they need to be able to run a small farm - two key challenges in Chubut are access to water and energy, which are key reasons why many families migrate to urban centres. Many of the students of the school are beneficiaries of the PERMER programme, however few of their HWS are still working. Using an open-source design (Piggott, 2013) and supported by the NGO 500RPM, penultimate year students built a HWS and installed it at the school for demonstration and study. The next year, they constructed another HWS at the home of one of their classmates. The following year, these students taught the next cohort to build another HWS and carried out maintenance on the HWS they installed previously. This has continued to the present day, resulting in the manufacture, installation and maintenance of 6 HWS. This bottom-up approach to building decentralised technical capacity is laying the foundation for a much more sustainable future small wind electrification programme. At the time of writing, the agro-technical school are considering options for scaling-up the initiative, including forming a new co-operative among the students to offer maintenance services commercially, partnering with existing cooperatives, replicating the initiative in other schools and establishing formal links with the PERMER programme.

In Chubut, this low sense of ownership was also found to contribute to the failure of systems through misuse and robbery of equipment. For example, bypassing the low voltage disconnect designed to protect batteries, using batteries in trucks or selling them on and even suspected robbery by thieves impersonating DGSP staff claiming to be dismantling the system in order to take it back to

[30] Approximately £4000 ($10,487 in 2008 USD).

[31] The Proven WT2200 was first upgraded to the Proven WT2500 in the late 90s, which then became the Kingspan 2.5 kW. In 2012, the SWT alone sold for £7000 ($12,511 in 2008 USD).

Rawson. Some users even saw the SWT as a foreign object taking up space on their land:

"The turbine doesn't mean much to me, it's more of an ornament."
[Chubutense farmer & PERMER-Chubut beneficiary, September 2014]

In contrast, whilst there were still cases of failures due to misuse in the Falklands, most users were found to be "quite careful with [their HWS] as they know that if it goes down, they lose out" (Falkland Island farmer & FIDC Beneficiary, August 2014). The fact that farmers had to actively make the decision to invest significant amounts of their own money in the equipment was found to be extremely important in establishing ownership. As a result, the majority of HHs were willing to adapt their daily practices around the availability of renewable resources: "you look out the window & if that turbine's going round something wicked, you stick the electric kettle on!" (Falkland Island farmer & FIDC Beneficiary, August 2014).

In the Falklands/Malvinas, wind power has been successfully used to reduce diesel fuel consumption at a variety of scales. From the 1.9 MW wind farm that is integrated into Stanley's diesel mini-grid, to the 12 kW of wind power at the Fitz Roy farm micro-grid and all the way down to the 2.5 kW Provens that have become standard issue across the islands' small farms. Although some standardisation of equipment was essential to mitigate the long supply chains inherent in all aspects of Falkland Island/Malvinense life, each system was designed to match the scale of demand and interconnectivity requirements of each particular settlement. In fact, in Chubut, several utility-scale wind farms had also been developed in parallel to the HWS. CREE had negotiated with the developers to channel funding through their Corporate Social Responsibility (CSR) programmes into addressing the neglected HWS. Specifically, they had hoped to open a factory producing batteries in Gastre, however for undisclosed reasons, pressure from the political 'regime' level prevented this from happening.

Appendix D. Detailed analysis of critical technical factors

In Argentine Patagonia, the arid steppe climate (<200 mm/yr rainfall (MEM, 2015)) that dominates the vast majority of the region keeps vegetation low, allowing the relentless winds rolling over the *cordillera de los Andes*[32] to whip across to the coast virtually unobstructed. However, the Atlantic Ocean allows them to accelerate even further before they hit the Falklands/Malvinas. In Chubut, a significant proportion of the population live in valleys (where there is a reliable water supply), however the valleys themselves, as well as the trees that grow in them (either naturally or planted to give shelter) create significant shelter and turbulence, which both reduces energy yields and leads to more frequent failures. What is more, Fig. 6 shows that the Eastern and Western frontiers of the province have significantly lower wind resources than the central region. In contrast, very few trees at all exist in the Falklands/Malvinas, with north-easterly slopes offering the only slightly sheltered regions. In fact, the few that do, had been planted by settlers in an attempt to shelter the spaces they inhabit and are flagged almost beyond recognition, stripped of almost all branches on the windward side.

In the Falklands/Malvinas, HWS were designed to address the weaknesses of diesel generators. The battery/inverter system upgrade allowed farmers to operate their generators for fewer hours at higher load factors, increasing efficiency (see Fig. 12) and decreasing wear, whilst at the same time offering 24 h power. The optional SWT upgrade reduced generator running hours and fuel consumption even further. The Trace SW Power Centre offered seamless hybridisation, automatically starting the generator for large loads or low state of charge. As a result, Falkland Island/Malvinense farms almost never suffered total power outages. At the time that the FIDC grant scheme was first developed (mid-90s), the price of PV was still prohibitively expensive, however it has recently fallen significantly, with many users taking advantage of the modularity of PV to gradually increase the capacity of their systems.

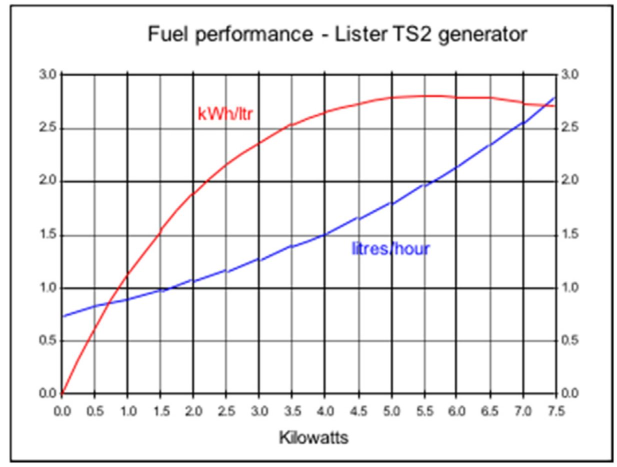

Fig. 12. Fuel consumption and energy conversion efficiency of the Lister TS2 used on many Falkland Island/Malvinense farms (Cotter, 1999).

The root cause of many of the failures observed by the research team during field visits in Chubut can be attributed to the Eolux G2 A500's reliance on a single manually operated friction brake, similar to a bicycle V-brake.[33] Whilst this may have sufficed in the lower wind sites typical of Northern Argentina where the Giacobone factory is located, it offered inadequate protection for the extreme wind speeds seen across Patagonia. The retaining spring that holds the brake off until activated by the user is a consumable part, that will fail if not maintained, leaving the SWT permanently braked. However, more destructive failures often occurred:

"the brake pads wear out and the wind turbines cannot be braked… so they are blown apart….the brake system is something so simple and so easy to fix…it drives us crazy!"
[DGSP, Chubut, September 2014]

Users were instructed to pull the brake lever at the bottom of the tower if they knew a storm was coming, but even if the brake is in full working order, this protection mechanism is rendered obsolete if nobody is at home when the storm hits. SWTs left to run free in storms are in danger of burning out electrical components due to overcurrent or destroying mechanical components due to over-speeding and excessive vibration. As there are no other generation sources on the PERMER-Chubut systems, the batteries quickly discharge. When left discharged for many months, the battery's active material is permanently destroyed,[34] meaning that the bill for repairing a system in this state is comparable to purchasing an entire new system.

What is more, the fact that the batteries were left outside in sealed containers would only have shortened their lifetime further, as the electrolyte could not be topped up and both diurnal and seasonal temperature oscillations in central Chubut's arid steppe climate can be extreme (down to −30 °C in winter and up to 35 °C in summer). In contrast, the

[32] Mountain chain defining Argentina's border with Chile.

[33] At the time of writing, Eolux, had recently developed a dynamic brake (furling mechanism) that can be retrofitted to any of the 1500 PERMER systems. Such mechanisms have already been widely adopted by many small wind manufacturers across the globe and protect the SWT passively by allowing the blade hub to fold onto the tail under the force of high winds, thus orienting the rotor perpendicular to the current wind direction and greatly reducing the relative wind speed that the rotor sees.

[34] During prolonged discharge, the amorphous lead sulphate produced during the normal operation of lead acid batteries deposits as a stable crystalline on the negative plates, reducing the battery's active material and setting into an irreversible state after several weeks or months.

sea regulates extremes of temperature in the Falklands/Malvinas and battery sheds were often heated either directly or indirectly by generator exhausts. Falkland Island/Malvinense farmers 'religiously' topped up battery fluid levels, allowing the high quality tubular Chloride Motive Power batteries to last well over the expected 10 years (in fact, even if any of the individual 2 V cells started to show signs of weakness, they could be pulled out and replaced, allowing the rest of the battery bank to continue operating for many more years). In the Falklands/Malvinas, many components exceeded their expected lifetime, as simple yet robust equipment that is appropriate for high wind sites was carefully selected by programme designers and regular maintenance check-ups[35] were able to prevent minor failures from becoming catastrophic disasters.[36] However, it should be noted that maintenance requirements were still considered high by many users who paid for private companies to carry out the check-ups and when they do occur, catastrophic failures are extremely expensive.

Furthermore, based upon observations during the field research, the technical design of the wind turbines used in the Falkland Islands has a key advantage: Proven's 6 m tilt-up towers can be lowered by anybody with a Land Rover, which allowed solidarity between farmers to play an important role. It was observed that neighbours with technical skills were often willing to lend a hand and further reduce the need for lengthy and costly trips out from Stanley (which like Rawson, is located in one corner of the area it governs). However, Eolux's 12 m lattice towers require specialist equipment and training to climb up and access the SWT, further entrenching the dependency on an external maintenance network.

Appendix E. Detailed analysis of critical political factors

In both regions, sovereignty disputes have precipitated national policies supporting the settlement of rural areas. In 19th century Chubut, parcels of land were given away to new settlers in order to reinforce Argentina's sovereignty in a region disputed between the newly formed states of Argentina and Chile, as well as First Nations, in particular the Mapuche. In this arid region, sheep farming was one of the few profitable livelihoods, which lead to the establishment of many of the *estancias* (farmhouses) that are scattered across the region today. Political support for residents of Argentina's Patagonian region continues to the present day in the form of state subsidies and infrastructure development. Although the Falkland Islands/Islas Malvinas had no indigenous population, the sovereignty dispute between Argentina and the United Kingdom, which lead to the 1982 conflict, has resulted in the development of similar political support for rural livelihoods.

This has favoured the development of HWS, directly through the development of rural electrification programmes, and indirectly through the establishment of supporting infrastructure. For example, whilst many Falkland Island/Malvinense farms could previously only be reached by boat, significant investment in transportation infrastructure (a road network and heavily subsidised flights) has made access to each farm for the installation and maintenance of HWS much easier. However, it should be noted that in Chubut, the size of the off-grid population is still decreasing rapidly, not just due to rural to urban migration, but also due to investment in grid infrastructure, connecting up the many formerly diesel-powered settlements across the region, as well as any isolated HH that happen to lie en route.

Despite the large number of failures seen in Chubut, Eolux is considered to be one of the most reliable machines available on the Argentine market. However, on the socio-technical 'regime' level during the time of the research, the market was protected from overseas competition by high import taxes and long delays in customs. The lack of choice of reliable equipment for extreme conditions on the Argentine market can be partly attributed to the limited size of the domestic market (to which manufacturers are largely confined to due to the inability to compete in markets with unrestricted imports), which is purely off-grid as there is currently no feed-in tariff. Today, most potential customers in the Argentine market (i.e. people without access to electricity) live outside of Patagonia and have low ability to pay. Therefore, Argentine SWTs have naturally evolved to meet the needs of this market segment, i.e. lowest possible initial cost and only needing to survive the less challenging environment further North. Redesigning a machine for the harsh Patagonian environment requires significant investment and cannot be justified unless there is a proven market and time to carry out the necessary research and development, something that the restrictions imposed by the GEF/World Bank grant did not allow.

[35] Lower tower, check (& change if necessary) springs & nylon rods in coning mechanism, slip ring brushes, rubber blade gussets (flexible root of blade that allows coning, but is susceptible to perishing) & yaw rollers, greasing main & yaw bearings & tightening all bolts. Revise electrical system, clean corroded connections & top up battery fluid levels.

[36] Common failures before the expected end-of-life included blades cracking and filling with water, springs pinging off the coning mechanism and core meltdowns. Whilst the former two failures could easily be repaired by a technician or even in some cases by well-trained users, the latter was far more disastrous. Fortunately it only affected a small batch of turbines installed around 2010. The issue was caused by switching to a new compound used in the stator resin, which was cheaper, but had a much lower thermal dissipation, meaning that on high wind sites, the core of the machine would either catch fire and/or melt and drip out of the bottom of the machine. After the bankruptcy of Proven, this issue was fortunately resolved by Kingspan, who reverted back to the old compound and thicker windings for improved heat dissipation.

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